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UPLAND TERRACES IN SOUTHERN NEW ENGLAND

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ABSTRACT

Recognition of the forms present has been the basic difficulty in the interpretation of New England geomorphic history. Joseph Barrell's recognition of broadly developed multiple terraces of marine origin is shown to be erroneous, since the existence of the terraces was concluded from incomplete evidence and questionable logic.

Multiple facets, as recognized by Douglas Johnson, can be observed directly on suitable profiles and to some extent in the field. These real forms indicate that New England has undergone complex peneplanation. Such a history is entirely compatible with the hypothesis of regional superposition applied to adjacent Appalachian areas.

INTRODUCTION

The New England Upland long has been a testing ground for many concepts of cyclic and noncyclic denudation. It still is being used for that purpose, for after forty-five years of research there is disagreement as to its geomorphic history.

The broad rolling surface of the crystalline rocks in western Connecticut was cited by W. M. Davis[1] as a good example of an uplifted, dissected peneplain of fluvial origin. This interpretation was challenged by R. S. Tarr,[2] who suggested the alternate hypothesis of noncyclic beveling. Davis replied, showing that noncyclic beveling could not adequately account for the subdued upland.[3] Since that time there has been general agreement that the upland is the result of cyclic processes, although few geomorphologists accept Davis' original interpretation of the surface as a single peneplain warped down more steeply near the Connecticut shoreline.

The earliest modification of the single-peneplain concept was proposed by Joseph Barrell.[4] He suggested that, although a peneplain had once been formed, it had largely been destroyed by later marine and fluvial erosion. According to Barrell, the present surface is not one peneplain but a series of seaward-sloping, dissected marine planes stepping down to the sea at intervals of from 100 to 400 feet. These dissected terraces were more fully described in a later paper.[5]

[1] "Physical Geography of Southern New England," *Nat. Geog. Soc.*, Mono. I, No. 9(1895), pp. 269–304.

[2] "The Peneplain," *Amer. Geol.*, Vol. XXIII (1898), pp. 351–70.

[3] "The Peneplain," *Amer. Geol.*, Vol. XXIII (1899), pp. 207–39.

[4] "Post-Jurassic History of the Northern Appalachians," *Bull. Geol. Soc. Amer.*, Vol. XXIV (1913), pp. 690–91.

[5] Barrell, "Piedmont Terraces in the Northern Appalachians," *Amer. Jour. Sci.*, Vol. XLIX (4th ser., 1920), pp. 227–58, 327–62, and 407–28.

Barrell's hypothesis of multiple marine planation virtually denies the preservation of a broad upland peneplain in New England. Other workers have modified Davis' hypothesis of a single warped peneplain in a different manner. According to H. S. Sharp[6] and Douglas Johnson,[7] the upland consists in the south of an older resurrected peneplain, but farther north it is a younger surface which had never been covered by later sediments. Johnson[8] has recognized that the upland possesses additional complexities which have not yet been fully studied. He doubts the marine origin of certain terrace-like forms on the following grounds: (1) The faint inclination of the supposed cliff zones are unlike any authentic marine forms. (2) The supposed sea cliffs are more faintly inclined than many hill slopes not regarded by Barrell as terrace remnants. (3) Slopes similar in form to the supposed sea cliffs face inland, away from the ocean. (4) The terraces are not recorded on Mount Desert Island, Maine, where the situation is favorable for their retention.[9]

G. W. Stose[10] has returned to the original interpretation of Davis for the New Jersey–Pennsylvania region and holds that a single warped peneplain is present. His interpretation is based chiefly on stratigraphic evidence gathered from the adjacent coastal plain, which would presumably apply to near-by New England.

H. A. Meyerhoff[11] suggests that the supposed resurrected pre-Tertiary peneplain near the Connecticut shoreline is, instead, a Miocene marine erosion surface with some lower marine benches of later date.

Such are some of the conflicting views now held concerning the cyclic history of New England. Part of this conflict originates from different methods of observation, which lead different observers to believe in the existence of different forms. The rest of the conflict arises from the fact that various interpretations have been offered for the same forms. It is the purpose of this paper to re-examine the New England Upland, to evaluate the methods of observation employed by different investigators, and, if possible, to determine what significant forms are actually present. When this has been done, it will be pertinent to examine those hypotheses which seek to explain the forms recognized. By following this procedure some resolution of conflicting ideas may be achieved.

The interpretation of broad upland surfaces cut across complexly folded crystalline rocks, like those in southern New England, not only should be made on the basis of local evidence but should be compatible with regional histories of adjacent areas.

The studies of Douglas Johnson,[12] Karl Ver Steeg,[13] and others indicate fairly conclusively that in the adjacent portions of the Appalachians the erosion surfaces are of fluvial origin. The low descent of monadnock ridges toward present water gaps, described by Ver Steeg,

[6] "Physical History of the Connecticut Shoreline," *Conn. State Nat. Hist. and Geol. Surv. Bull. 46* (1929), pp. 34–50.

[7] "A Theory of Appalachian Geomorphic Evolution," *Jour. Geol.*, Vol. XXXIX (1931), pp. 497–508; *Stream Sculpture on the Atlantic Slope* (New York: Columbia University Press, 1931).

[8] "Appalachian Studies I" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. XL (1929), pp. 131–32.

[9] P. 7 of ftn. 7, *Stream Sculpture . . . .* (1931).

[10] "Age of the Schooley Peneplain," *Amer. Jour. Sci.*, Vol. CCXXXVIII (1940), pp. 461–76.

[11] "Tertiary Marine Planation in the Piedmont and Southern New England" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), pp. 1954–55.

[12] Ftn. 7, *Stream Sculpture . . . .* (1931).

[13] "Wind Gaps and Water Gaps of the Northern Appalachians," *N.Y. Acad. Sci.*, Vol. XXXII (1930), pp. 87–220.

indicates that shallow water gaps existed at these sites on the Schooley peneplain and that a later marine invasion was never instrumental in affording a sedimentary cover thick enough to permit shifting of stream locations.

Johnson has shown that the existence of wind gaps in line with southeast-flowing streams indicates a regionally superposed drainage which has undergone disruption on a large scale without interruption by marine transgression since Schooley time.

If the Schooley peneplain can be traced into the New England Upland, then it would seem reasonable that surfaces in New England should be of fluvial origin and that the hypothesis of regional superposition, as outlined by Johnson, should find application.

The studies of Joseph Barrell indicate that any fluvial peneplains which may have been formed in New England have been largely destroyed and replaced by a series of broad, shallow terraces cut by marine agencies. This hypothesis of marine terracing is evidently incompatible with that of regional superposition as applied to the adjacent Appalachians, for it is difficult to see how the region immediately west of the Hudson River could have had a fluvial history while at the same time the area immediately east had a marine history.

The present study is not merely an effort to demonstrate the presence or absence of marine terraces but also an attempt to judge between two hypotheses. If marine terraces exist in southern New England, then serious doubt must be thrown on the hypothesis of regional superposition as applied to this and the adjacent Appalachians. If forms in New England can be assigned a simple fluvial origin, then further support is added to the hypothesis of regional superposition.

LOCATION OF THE AREA STUDIED

The present examination of surface forms has largely been confined to the Western Upland of Massachusetts and Connecticut (Fig. 1). The area is roughly bounded on the north by the Massachusetts-Vermont border, on the east by the Connecticut Triassic Lowland, on the south by Long Island Sound, and on the west by the New York State line. In this area all the forms involved reach their most typical development. Here the best remnants of Barrell's supposed terraces are located. If they can be shown to indicate marine planation, then studies may be extended to the Eastern Upland, where, according to Barrell, terraces were weakly developed or poorly preserved. If the terraces do not stand analysis in the Western Upland, there is

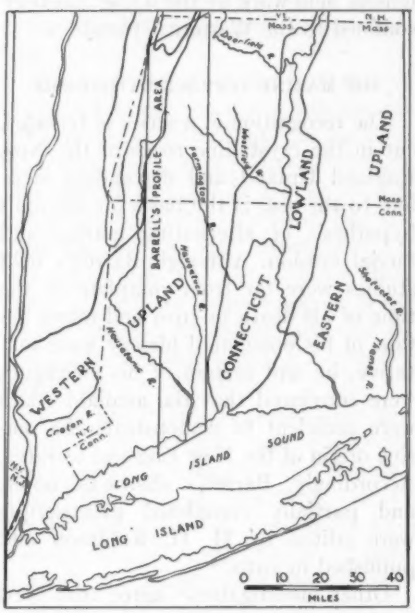

FIG. 1.—Index map

little chance of finding critical evidence elsewhere in New England.

The surfaces described by Douglas Johnson are also well developed in the Western Upland. But since they extend southwest to the Manhattan prong of the New England Upland and eastward to the Eastern Upland, it will be necessary to consider those areas where additional data are required. The most intensive field work by the writer has been confined to the Western Upland.

THE MARINE-TERRACE HYPOTHESIS

The recognition of a series of terraces, cut in the crystalline rocks of the New England Upland and descending steplike to the sea, is the basis for Barrell's hypothesis of alternating marine and fluvial erosion. Although Barrell's field studies were far from complete at the time of his death in 1919 and many details of his postulated history were tentative, he and certain of his colleagues were convinced that the available data were sufficient to demonstrate the marine origin of the New England terraces. Accordingly, Barrell's abstracts, notes, and partially completed manuscripts were edited by H. H. Robinson and published in 1920.[14]

Other investigators[15] agree that New England and the adjacent area exhibit multiple terraces. Some variation is introduced in connection with higher terraces, which are generally considered to be fluvial in origin. None of these investigators attempts a critical analysis of the data upon which their conclusions rest. A paper by J. L. Rich[16] appears to accept Barrell's terraces but offers a somewhat different history to account for their preservation.

In view of the importance assigned to these supposed terraces, it appears necessary to subject the evidence for their existence to a more careful scrutiny than has heretofor been attempted.

DEVELOPMENT OF BARRELL'S HYPOTHESIS

Barrell, working on the physiography of the Housatonic folio in 1909–10, did not recognize marine terraces but interpreted the landscape in terms of the upland and lowland peneplains of Davis. In 1911 field work in western Connecticut and southwestern Massachusetts led to the same interpretation. Barrell was, however, on the watch for a Cretaceous shoreline, since he had presented evidence that Cretaceous beds had formerly extended farther inland than their present outcrop in adjacent areas. Seeking to determine the elevations of the accepted peneplains and possibly to find the expected shoreline, Barrell[17] constructed a projected profile covering a broad zone in southwestern Connecticut. This profile showed a pattern which could be interpreted as a series of steps or terraces. Extension of similar profiles

[14] Barrell, "Piedmont Terraces in the Northern Appalachians," *Amer. Jour. Sci.*, Vol. XLIX (1920), pp. 227–58, 327–62, and 407–28.

[15] Laura Hatch, "Marine Terraces in Southeastern New England," *Amer. Jour. Sci.*, Vol. XLIV (1917), pp. 319–30; Florence Bascom, "Cycles of Erosion in the Piedmont Provinces of Pennsylvania," *Jour. Geol.*, Vol. XXIX (1921), pp. 540–59; E. B. Knopf, "Correlation of Residual Erosion Surfaces of the Eastern Appalachian Highlands," *Bull. Geol. Soc. Amer.*, Vol. XXXV (1924), pp. 633–88; A. M. Pond, "Preliminary Report on the Peneplanes of the Taconic Mountains of Vermont," *16th Ann. Rept. Vt. State Geol.* (1927–28), pp. 292–314; H. A. Meyerhoff and M. Hubbell, "The Erosional Landforms of Central Vermont," *16th Ann. Rept. Vt. State Geol.* (1927–28), pp. 315–81.

[16] "Recognition and Significance of Multiple Erosion Surfaces," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), pp. 1695–1721; see especially pp. 1714–17.

[17] "Geologic History of the Archean Highlands of New Jersey" (unpublished Master's thesis, Yale University, 1896), chap. viii, Part II.

over the whole western upland led Barrell to the conclusion that eleven benches, all of marine origin, could be distinguished.

The work thus started in New England was extended to the Maryland Piedmont and Coastal Plain. Here Barrell, using similar profiles, found similar benches which he correlated with the numerous unconformities in the coastal-plain sediments. The Piedmont benches trend parallel to the structure and could thus be explained by structural control. This was not believed to be true for the New England terraces, which were thought to be oblique to the structural trends, which are themselves oblique to the shoreline. Barrell found that the elevations of the New England terraces roughly coincided with those in Maryland, and from this he concluded that the structural control of the Maryland terraces was more apparent than real. He also believed that unconformities in the coastal-plain sediments could be used to date the terraces in both areas. On the basis of the terrace levels and unconformities, Barrell worked out the following tentative history for New England.

The sea advanced over the Cretaceous peneplain to the base of the Mount Greylock monadnock in Massachusetts, to cut the Becket terrace, now 2,400 feet above sea-level. This terrace was believed to be higher than the peneplain, which was considered to be partly preserved at an elevation of about 2,000 feet in an area east of the Hoosac Range and near the Deerfield River.

A slight emergence and subsequent stability resulted in cutting of the Canaan terrace, now at 2,000 feet.

A much greater emergence then caused the shoreline to retreat far to the south, somewhere beyond the present shoreline. The emergence was followed by mature fluvial dissection.

The sea then advanced over the maturely dissected land, which later remained stable long enough to permit marine agents to cut the Cornwall terrace, now at 1,720 feet.

The sea next retreated to the vicinity of the present shoreline, and streams again maturely dissected the land. Later submergence permitted marine agents to cut the Goshen terrace, now at 1,380 feet.

The terraces below the Goshen level are ascribed to successive emergences, with the possibility that the last four may have been due to eustatic changes. The names and levels are as follows: Litchfield, 1,140 feet; Prospect, 840 feet; New Canaan, 380 feet; Sunderland, 240 feet; Wicomico, 120 feet. The elevations given are for the inner margins of the terrace treads. All the terraces are described as sloping seaward between 2 and 8 feet per mile.[18]

It is important to remember that many of the terraces were supposedly formed after submergence of a maturely dissected land mass. Wave-cut terraces should, under these circumstances, have been developed first on islands and headlands. If the marine cycle progressed to maturity, the terraces should have become more continuous. But any such continuous terraces, if they ever were formed in New England, must since have been badly cut to pieces by stream dissection. In the nature of the case, therefore, it is impossible to determine whether the terraces were continuous at the time of their formation. Whether or not there was original continuity, the terraces today must be recognized, if at all, by remnants which are small in proportion to the intervening areas.

[18] Barrell, pp. 413–16 of ftn. 5 (1920).

If remnants of this kind are to be used to fix the positions of former shorelines, it must be demonstrated that they are of marine origin. A fair test of the marine origin of cliffs and benches may be applied by considering the effects of marine erosion on present shorelines and the results of later elevation of these features. With a clear idea of what should be expected to demonstrate the marine origin of cliffs and benches, it will then be appropriate to consider evidence for New England.

CRITERIA FOR THE RECOGNITION OF ELEVATED MARINE CLIFFS AND BENCHES

Elevated marine shorelines, developed on a formerly submerged sloping upland of complexly folded crystalline rocks, might be recognized by the following features:

1. *High-level benches which abut against steep cliffs.*—Such benches may be used if they bevel the structure and have considerable areal extent. Small local benches abutting against steep cliffs and beveling structure may arise from numerous fortuitous causes, such as jointing, exfoliation, slumping, et cetera—common in regions of complex structure. Minor benches, therefore, have no value as shoreline indicators. If large benches have been formed but later have been cut up by stream erosion, and the resulting hills are rounded by weathering, they are without value as indicators of former sea-levels, since there is nothing left to distinguish such hills from other rounded hills in the region. Isolated benches far from the supposed sea cliffs cannot fix the elevation of a former shoreline, since the bench may have been developed at an unknown depth below the supposed marine level, depending on the slope of the marine profile of equilibrium. All benches should slope seaward if they are of marine origin and have not been reversed in slope by subsequent warping.

It must also be shown that neither the bench nor the adjoining cliff has had its development controlled by structure or changes in rock type. Benches and cliffs attributable to such origin must exhibit specific marine features (undoubted wave-cut notches, sea caves, stacks, or marine deposits) before they can be used as shoreline indicators.

In judging the value of benches as evidence for former shorelines, the benches in question should be compared with others of similar size but so located as not to lend themselves to the marine interpretation. If it be found that the area contains similar or better benches at different elevations than those in question, or has similar benches facing away from the sea, or occurring in narrow estuaries, or sloping landward, then the value of the original benches as indicators of former shorelines is doubtful. This must be true when there is nothing to distinguish the benches attributed to marine action from others in the area which cannot be so interpreted.

If a broad, seaward-sloping bench is present, it should not be separated from the adjoining cliff by a sharply localized depressed area, unless such areas are underlain by weak rocks. Otherwise, it is highly improbable that the inner margin of a marine bench would be separated from its adjacent sea cliff by later fluvial processes before other parts of the bench were destroyed. The inner margin of a wave-cut bench normally has a steeper slope than parts farther out, is veneered with marine sand or gravel, and, when the sea withdraws, is likely to be protected by talus and slopewash from the sea cliff. Under these conditions streams should have great difficulty in

isolating the bench from the cliff unless the line of contact follows some structural or compositional weakness. If a weak zone is present, specific marine erosional features must be found before one may use the bench as an indicator of a former shoreline. Numerous depressions separating cliff from bench, where no marked structural weakness is present, are strong evidence against the marine hypothesis.

2. *Cliffs whose marine origin is adequately attested by the presence of wave-cut notches, sea caves, and stacks.*—Weathering and erosion may in time destroy notches and sea caves in a true marine cliff. In such event the marine origin of the cliff is difficult to demonstrate. This is especially true if the region exhibits abundant similar cliffs whose bases are at many levels different from those attributed to marine erosion or in positions not exposed to effective wave attack. Hills interpreted as stacks or offshore islands should rise from seaward-sloping benches.

CORRELATION OF TERRACE REMNANTS

If in a given region there are benches and cliffs which measure up to the standards enumerated above, it may fairly be concluded that marine erosion has modified the region to the extent indicated by the specific remnants. If the remnants are closely spaced areally and if their inner marginal elevations are accurately determinable, it may be possible to connect adjacent remnants to establish a former sea-level, if not a former shoreline. Such former sea-level positions may now be either horizontal or inclined, depending on whether crustal warping has affected them.

If the marine-terrace remnants are widely spaced, under no circumstances is it permissible to join such remnants with horizontal lines to support the interpretation that the terraces were once continuous and are oblique to the structure. Such lines are drawn on the basis of two assumptions: first, that the terraces were formerly continuous and, second, that they were uplifted without warping. Since neither of these two assumptions can be verified, any such lines must be considered as purely imaginary and as having no known relation to topographic or geologic elements. These lines, being imaginary, cannot be used as supporting evidence for the marine hypothesis, even if they do run oblique to structural trends. The marine hypothesis must be judged solely on the basis of the individual remnants of benches and cliffs.

If the remnants are widely spaced, it should be evident that many different correlations of the individual remnants may be possible under various assumptions of differential uplift. And if many correlations can be made, none of the restorations is a safe indicator of former sea-level, much less of the position of a former shoreline.

With these considerations clearly in mind, we may proceed to examine the evidence for the marine hypothesis in southern New England.

ANALYSIS OF LABORATORY EVIDENCE

Barrell's studies succeeded in emphasizing one point upon which there is general agreement: that the upland is not a smoothly sloping, dissected plane. That fact is amply attested by profiles and by field observations. Not only do the regional slopes vary in direction and amount, but there are many localized undulations in areas where the regional slope is fairly constant. Before any of these local undulations are accepted as remnants of marine terraces, it must be

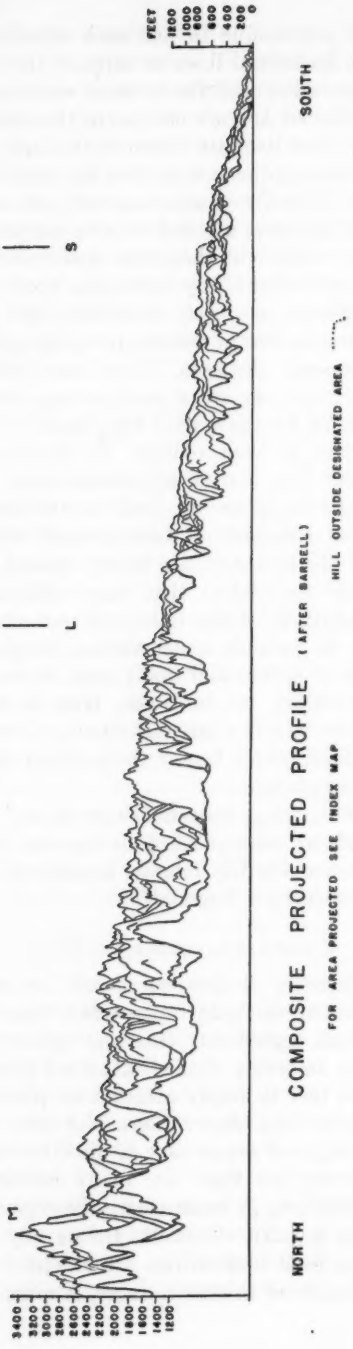

FIG. 2.—Composite projected profile (after Barrell)

shown that specific evidence exists which admits of no other interpretation.

Since the marine-terrace hypothesis as applied to New England was born from the study of maps and profiles, an analysis of this method of study is of primary importance.

The regional profile used by Barrell was of the projected type and covered an area in Massachusetts and Connecticut from one to one and one-third quadrangles wide, extending from Mount Greylock, Massachusetts, to Long Island Sound (Figs. 1 and 2). Such a single projected profile will be called by the writer a "composite projected profile." The method of its construction is thus described in the text of Barrell's paper and in an editorial note by Robinson:

> A strip of cross-section paper is fastened parallel to the lower edge of a drawing board and the topographic sheet is fastened above so that the direction of view is at right angles to the length of the section and thus parallel to a T square placed against the lower edge of the board. The area to be projected is outlined and the contours which cut the front edge of the block are projected first to give the foreground. . . . . Then the topography beginning at the front and working toward the back of the block is systematically projected onto the cross-section paper with the aid of the T square. Each successive belt of topography *shuts out all behind it*[19] except the higher elevations, thus indicating what features are to be projected as the work progresses. . . . .
>
> [EDITORIAL NOTE (BY H. H. ROBINSON): It should be said in regard to projected profiles that they are objective with respect to summit elevations but that the slopes may or may not be truly shown. There is room to *exercise considerable judgment* in the selection of slopes. The case may also arise where it is *advisable to omit a prominent object* in the foreground because it hides too much of the country behind, or if it seems *desirable to retain it*,[20] the topography hidden by it may be indicated by a dotted

[19] Italicized by the present writer.

[20] Italicized by the present writer.

line. A projected profile . . . . calls for the exercise in some degree of the pictorial sense].[21]

The method outlined above is characterized by H. H. Robinson, the editor of Barrell's posthumous paper, as being "more free than others from the subjective defect of picking and choosing the facts." This is far from true, for several reasons. First, a direction of view is chosen "which is best adapted to show the character of the culminating upland surface, as to whether it is a plane or a series of planes." The fact that the investigator chooses a particular direction of view indicates the subjective basis of the procedure. He must have an opinion as to the presence of terraces and their trend before he can select the direction of profiling that will best reveal their character.

The statement that a test is being made between a "plane or a series of planes" is misleading. Actually the question is whether the surface is a peneplain or a series of planes. Purely local irregularities of a tilted fluvial peneplain may well appear as terrace-like forms where the direction of view is normal to the slope of the surface (Fig. 3). Profiles made in this direction are inadequate to distinguish between a sloping peneplain and a series of planes. They must be supplemented by other profiles, looking up the slope of the surface, before one can distinguish between local irregular swells on a peneplain and extensive, systematic terrace remnants.

Another subjective element in the composite projected profile is the retention or omission of hills according to "desirability." If such a choice is permitted the investigator, it seems inevitable that he must tend to omit hills which do not fit into the terrace picture and which obscure hills farther away that would fit into the picture. Certainly, this is "picking and choosing the facts" to be represented as of significant value. A really objective profile would show the upland hills without selection and would be constructed without any single hypothesis in mind.

The subjective nature of the composite projected profile is further indicated when it is noted that Barrell found it necessary to go beyond the area outlined for profiling to take in certain hills the inclusion of which strengthens the evidence for one of the terrace levels (Fig. 2). The need for going outside the stated area (a whole quadrangle) to find support for a terrace level implies not only that the evidence for that terrace is weak but also that a single hill or group of hills may, on the composite pro-

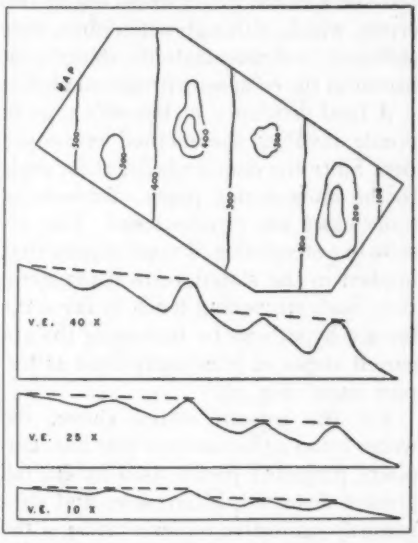

FIG. 3.—Composite projected profiles of scattered hills on a sloping plane, using vertical exaggerations of 40, 25, and 10 times (Barrell's method of projection). Dashed lines indicate the position of apparent dissected terraces. The hill slope appearing as the terrace riser seems to steepen as the vertical exaggeration is increased.

[21] Barrell, pp. 243–44 of ftn. 5 (1920).

file, give an appearance of terracing not supported by the topography as a whole.

An additional reason for doubting the efficacy of the composite projected profile is the dependence of the investigator on a single major projection. If errors in drafting are made, they may lead to erroneous interpretations upon which no check is available. In redrawing Barrell's profiles the writer found one or two errors, which, although not serious, were sufficient to demonstrate the dangers inherent in the composite projected profile.

A final deficiency in Barrell's type of profile involves the method of projection. Since the map is placed at an angle to the cross-section paper, distances in some cases are foreshortened. This results in a steepening of slope beyond that implied in the stated vertical exaggeration. Such steepening tends to favor the terrace hypothesis by increasing the apparent slopes of hills interpreted as terrace risers (Fig. 3).

For the reasons stated above, the writer is forced to conclude that the composite projected profile used by Barrell gives a distorted, incomplete, and dangerously subjective representation of the surface. By itself, such a profile indicates only certain topographic inflections, which may or may not be the product of terracing.

Barrell apparently realized some of the limitations of the type of profile he employed, for he supplemented the profile by tracing the supposed terrace levels across topographic maps of the region. This was done by connecting with continuous lines the inner margins of specific isolated "terrace remnants." The resulting regional terraces are shown in generalized form only, on a small index map (Fig. 1, Barrell). Unfortunately, terrace remnants are specifically named and located for but one small area. The other remnants must be searched for on topographic maps. By comparing these maps with Barrell's index map it has been possible to find most of the hills interpreted by him as terrace remnants, although some seem to be out of place and others could not be found.

It soon became apparent that the index map gives a false impression of the relative size and spacing of the supposed terrace remnants. This is because on the index map the symbols for the remnants are generalized and drawn on a greatly magnified scale, in order to make them clearly legible. Actually the remnants are very small in most cases, and the distances between them very great (Fig. 4, *A* and *B*).

As shown in the previous section, it is not permissible under any circumstances to assume that widely spaced terrace remnants can be joined by a line to indicate a former shoreline. Only when the marine origin of the remnants has been demonstrated and the proper correlation of these remnants has been fully established can a line connecting them be interpreted as marking a former margin of the sea. Barrell's strongest argument for the marine origin of his supposed regional terraces was that they cut obliquely across belts of varying resistance. But it should be fully appreciated that there are neither terraces nor terrace remnants traversing the lithologic belts of the New England Upland. The only things traversing those belts obliquely in a northeast-southwest direction are the lines of interpretation drawn by Barrell to connect isolated and widely spaced hill slopes regarded by him as terrace remnants.

EXAMINATION OF THE SUPPOSED MARINE-TERRACE REMNANTS

Since lines connecting supposed terrace remnants have significance as former shorelines only in case the remnants

can be shown to be of marine origin and in case the proper correlation of remnants can be fully established, it is pertinent first to examine the remnants, in order to determine their probable origin.

scarps and ridgetops which have been interpreted by Barrell as remnants of marine terraces.

Although several high-level benches appear on Barrell's profile, only small

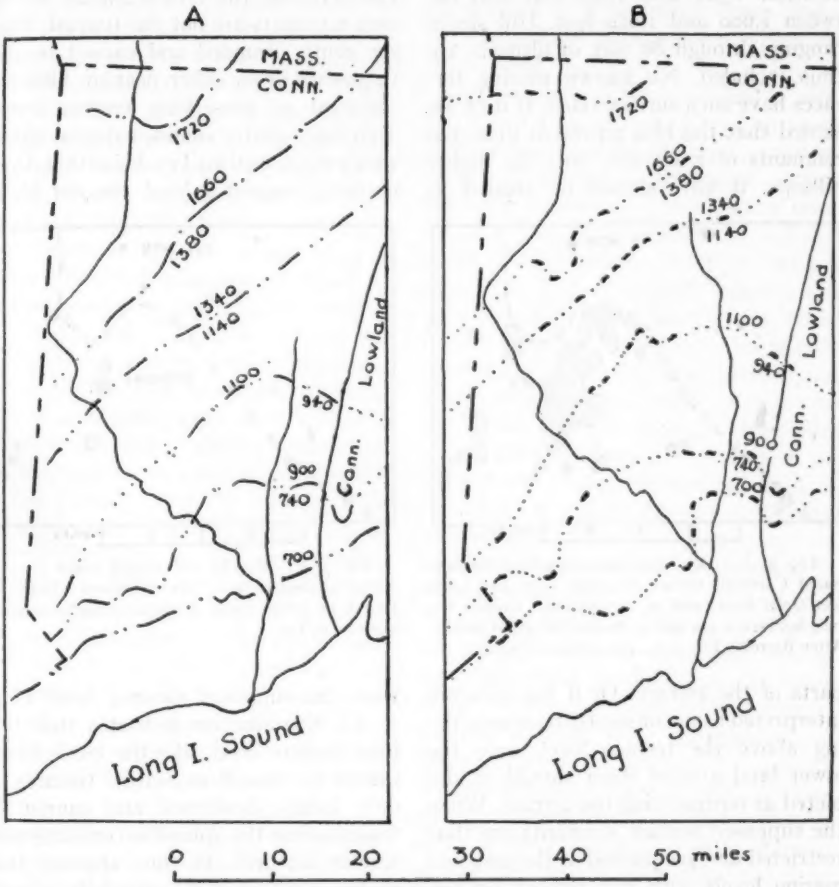

FIG. 4.—(*A*) Terrace restorations, redrawn from Barrell's "Piedmont Terraces," Fig. 1 (p. 247 of ftn. 5 [1920]). Long dashes represent stretches where the supposed terrace remnants are closely spaced but not necessarily continuous. Dots represent stretches where no remnants can be found. (*B*) The present writer's detailed plotting of supposed terrace remnants, taken from topographic maps.

The marine hypothesis can best be tested by applying the standards set up in a previous section to determine the marine origin of elevated cliffs and benches. We then turn to an examination of certain

areas of two supposed terrace remnants are illustrated with a map.[22] This map, reproduced here as Figure 5, *A*, shows a portion of the Goshen terrace believed

[22] *Ibid.*, p. 255, Fig. 6.

by Barrell to have its inner margin now at an elevation of 1,380 feet and a portion of the Cornwall terrace with an outer margin now at 1,680 feet. Shaded to represent terrace remnants are all areas between 1,300 and 1,380 feet and between 1,600 and 1,680 feet. Hill slopes ranging through 80 feet of altitude are thus included. No known marine terraces have such surface relief. If it be assumed that the hills represent dissected remnants of a terrace, only the higher hilltops, if any, should be shaded as parts of the terrace. Or if the hills are interpreted as unconsumed remnants rising above the terrace level, only the lower land around them should be depicted as representing the terrace. When the supposed terrace remnants are thus restricted and are plotted at the assumed marine levels with due respect for the seaward slope postulated by Barrell, the areal extent of the supposed Goshen "bench" remnants is so enormously diminished as to cast grave doubt on their significance (Fig. 5, *B*). The same must be true in even greater measure for other "bench" remnants less clearly developed.

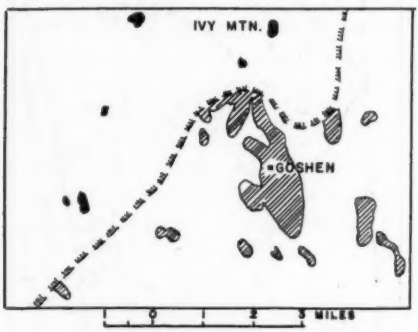

FIG. 5, *A*.—Map showing remnants of the supposed Cornwall terrace between 1,600 and 1,680 feet (*solid black*) and of the supposed Goshen terrace between 1,300 and 1,380 feet (*diagonal ruling*). After Barrell's Fig. 6 (p. 255 of ftn. 5 [1920]).

The remaining areas, interpreted as remnants of the Goshen terrace, nowhere abut against steep cliffs but are separated from the nearest scarps by valleys cut below the supposed marine level. Furthermore, the hills regarded as terrace remnants are not flat-topped. They are gently rounded and cannot be distinguished from other near-by hills not regarded as preserving marine levels. Two long, gently rounded ridges, one of which abuts against Ivy Mountain, Connecticut, suggest a level *100 feet higher* than the supposed Goshen level (Fig. 5, *A*). Examination indicates that this intermediate level, like the levels interpreted by Barrell as marine terraces, is only locally developed and cannot be traced across the upland to correlate with similar features. It thus appears that in the Goshen area, especially chosen by Barrell to demonstrate good marine terrace remnants, the existing hilltops and scarps fail to show any features which can safely be accepted as evidence of marine erosion.

Unfortunately, other bench areas are not figured in Barrell's paper. The writer has sought examples of flat areas of large

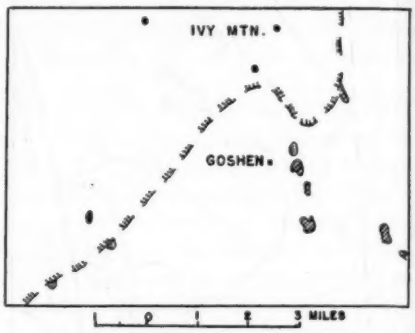

FIG. 5, *B*.—Map by the present writer showing actual summit areas at the elevations selected by Barrell as being those of terrace treads. Symbols same as in Fig. 5, *A*.

dimensions abutting against steep cliffs, sloping seaward and not controlled by structure and rock composition. No such features have been found. There are broadly rounded hilltops near the hypothetical shorelines; but these are off the assumed levels, are in the wrong position, or slope in the wrong direction to fit the marine-terrace hypothesis. It should be realized that most of the so-called "flat" areas referred to by Barrell[23] or interpreted from contour maps are, in reality, broadly rounded hilltops which need not imply the former existence of any bench or terrace tread. Most of these "flats" are separated from the nearest scarps by valleys—a condition not expectable under the marine hypothesis, for reasons earlier discussed.

Consideration of the areas cited above, as well as of other areas reported in this paper, and extended study of topographic maps lead to the conclusion that none of the broadly rounded hilltops show features confirming the marine-terrace hypothesis. Many of the best examples are above or below the supposed terrace levels. Others slope inland, and still others are in localities which would have been cut off from effective wave attack. In general, there is nothing which distinguishes the supposed sea cliffs and benches from any other cliffs and benches not regarded by Barrell as of marine origin.

In addition to the map of the Goshen area presented by Barrell and discussed above, several composite projected profiles of small areas are included in Barrell's paper on piedmont terraces. These profiles were especially chosen from a large number to show the best available benches and risers. Before discussing the individual profiles, it should be recalled that individual profiles of small isolated areas are not sufficient to demonstrate the regional nature of terraces. At best, they can only suggest possible marine levels. Such supposed marine levels must be adequately checked by profiles of intermediate areas to determine with what consistency they are maintained.

Examination of the published profiles (Barrell's Figs. 2, 3, 4, 7, and 8) raises doubt as to whether the topography indicates terracing of a marine nature. Barrell's Figures 2, 7, and 8 show areas on the Fall Zone where the regional slope is fairly steep—about 50 feet per mile (Fig. 7, *A*, of present report). The terraces are stated by Barrell to be weakly developed, most of them being considered as "re-entrant" and therefore not likely to show good breaks in slope on the profile. It may well be asked why poorly developed marine terraces in re-entrant areas should be selected for citation, since it is generally agreed that the earliest wave attack is concentrated on headlands and that major terracing is accomplished here.

Barrell's Figure 3 (Fig. 7, *B*, of present report) shows an area just west of the Connecticut Lowland near the inner margin of the Fall Zone. At first glance, the rise in slope from the 700-foot to the 900-foot level appears to support the marine-terrace hypothesis, because the rise is steep and joins broad, flattish areas to the north and south. Comparison of the profile with map and field data demonstrates defects of the composite projected profile and indicates that in this area there is little support for the supposed marine terrace. A hill erroneously labeled "Huntington Hill" (actually an unnamed ridge east of Straitsville) is located in an area that Barrell found necessary to include in his general profile in order to support the

[23] *Ibid.*, pp. 252 and 256.

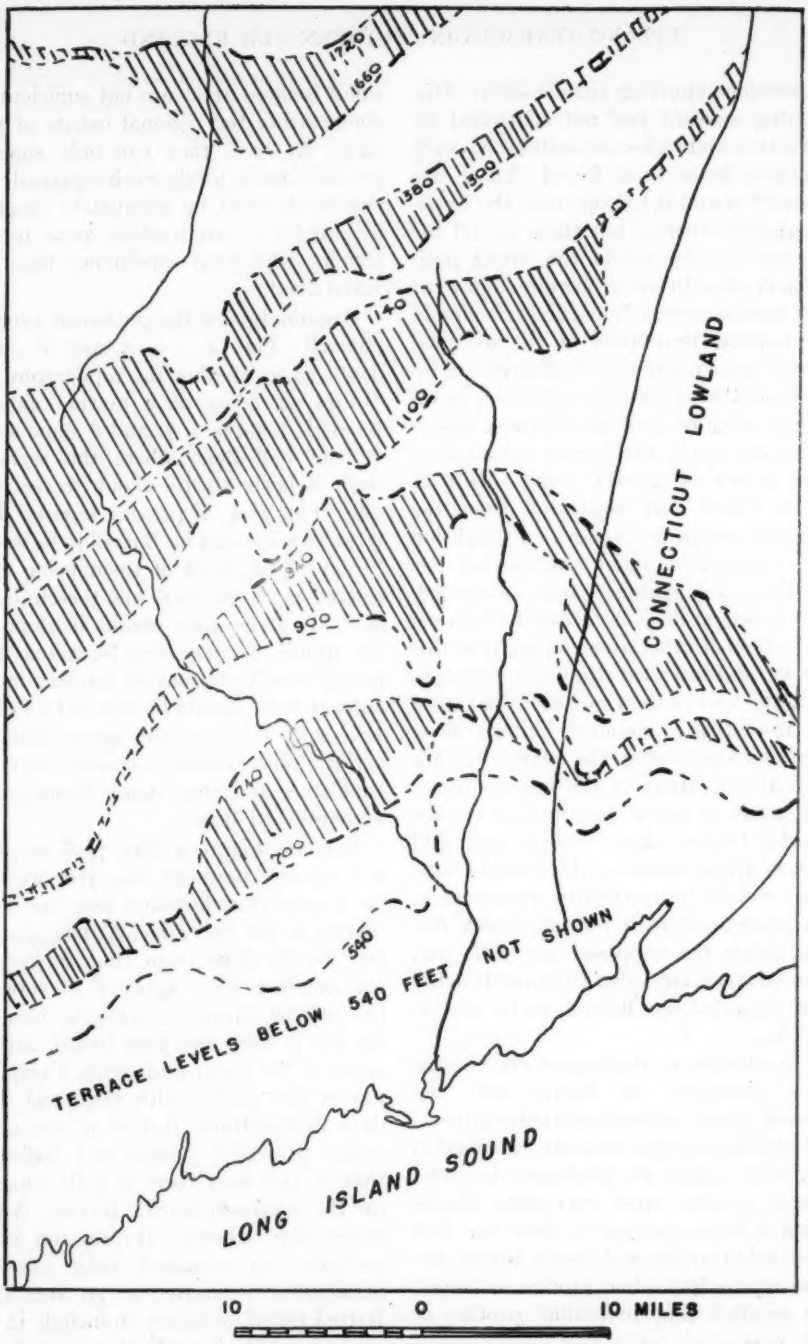

FIG. 6.—Widths of the supposed terrace zones in western Connecticut: supposed terraces—diagonally ruled; supposed risers separating terraces—blank. At only a few places are the terraces broad with respect to the separating risers. Riser slopes are predominantly gentle, as indicated by the great width of the riser zones.

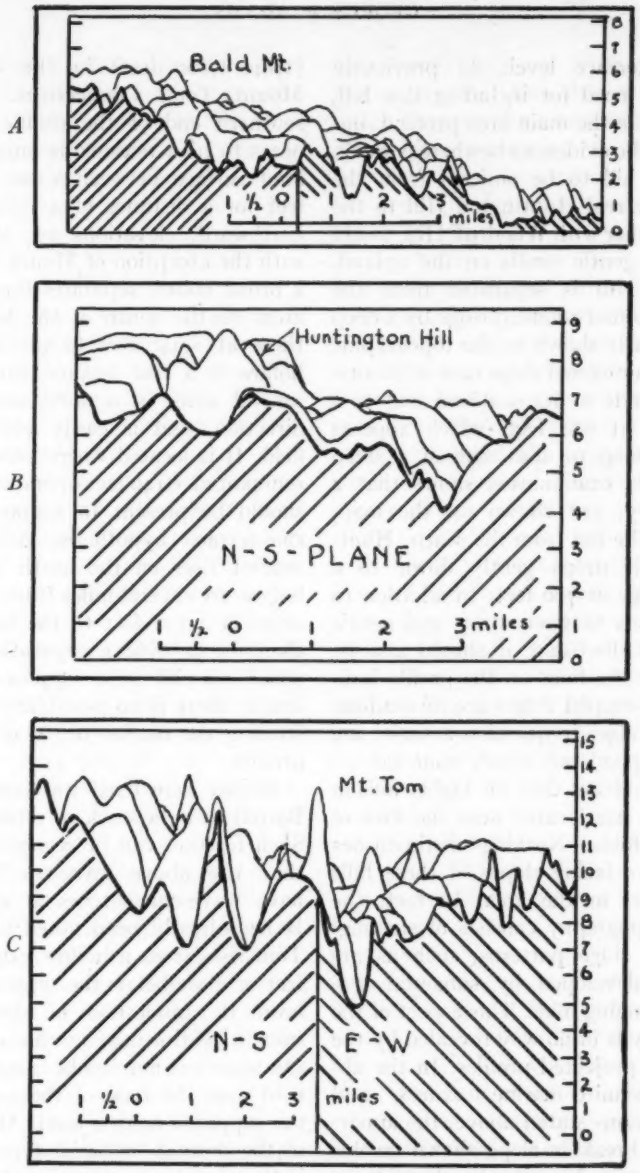
A
Bald Mt.
0 1 2 3 4 5 6 7 8
1 ½ 0 1 2 3 miles
B
Huntington Hill
N-S-PLANE
0 1 2 3 4 5 6 7 8 9
1 ½ 0 1 2 3 miles
C
Mt. Tom
N-S
E-W
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
1 ½ 0 1 2 3 miles

FIG. 7.—(*A*) Barrell's Fig. 2 (p. 252 of ftn. 5 [1920]). Projected profile of parts of the Stamford and Norwalk quadrangles, showing the Sunderland (200–240 feet), Pitcher Mount (280–320), New Canaan (340–80), and Appomattox (480–520) terraces. View looking N. 45° E.

(*B*) Barrell's Fig. 3 (p. 253 of ftn. 5 [1920]). Projected profile of parts of the Derby and New Haven quadrangles, showing the Towantic (700–740 feet) and Prospect (840–80 feet) terraces. View looking east. Huntington Hill is correctly located.

(*C*) Barrell's Fig. 4 (p. 253 of ftn. 5 [1920]). Projected profile of parts of the New Milford and Waterbury quadrangles, showing parts of the Litchfield (1100–1140 feet) and Goshen (1340–80 feet) terraces. View looking N. 55° E. (Captions taken directly from Barrell's figures.) Elevations given in hundreds of feet.

940-foot terrace level. As previously noted, the need for including this hill, lying outside the main area profiled, implies that the evidence elsewhere is weak. Were the hill to be omitted from the profile, the real Huntington Hill to the west, together with Woodruff Hill, would appear as gentle swells on the upland. Woodruff Hill is separated from the nearest 700-foot rounded ridge by a deep valley, clearly shown on the topographic map. The unnamed ridge east of Straitsville descends at its southern end to a small flat at 680 feet, which appears from the map to abut against a steep slope. Field examination shows that a deep valley, not shown on the map, separates the flat from the scarp. Huntington Hill drops gently down to a flattish ridge at 700 feet. In addition to the relations between steep and gentle slopes just discussed, it should also be noted that the lines on the profile indicating flat-topped ridges are misleading, since the ridges in question actually are not flat-topped but gently rounded.

It is significant that the higher hills in this region are located near the axes of plunging folds. Nothing distinguishes the seaward-facing slopes of these hills from others in the area. In fact, the general topography consists of strikingly curved ridge patterns, such as are normally developed by subaerial erosion of plunging folds. This aspect of the topography is in no way revealed by the composite projected profiles. In the absence of definite marine features, and for the reasons stated above, the apparent sharp break in slope shown on this profile cannot be considered evidence for a marine terrace.

Barrell's Figure 4 (Fig. 7, *C*, of present report) shows portions of the supposed Goshen terrace (1,380–1,340 feet) and the supposed Litchfield terrace (1,140–1,100 feet) in the vicinity of Mount Tom, Connecticut. Near the southern end of the profile there appears to be a reasonable amount of upland surface between 1,100 and 1,140 feet for a distance of 4 miles. Farther northward, elevations are lower; and, with the exception of Mount Tom itself, a broad hollow separates the 1,100-foot areas to the south of the hollow from those at 1,340 feet to the north. This hollow is a real feature, extending for several miles in a northeast-southwest direction, and is easily visible in the field. It is located where either a bench remnant at 1,140 feet or one at 1,340 feet should be present to support the marine-terrace hypothesis. Actually, the nearest rises on the north side of the hollow are several miles from the flattish areas at 1,100 feet to the south. Since there is so wide a separation of supposed sea cliff from supposed wave-cut bench, there is no possibility of demonstrating the marine origin of the forms present.

Mount Tom itself was considered by Barrell to be a stack or offshore island. Such features can be recognized only if they rise above wave-cut benches or have wave-cut notches at their bases. It has already been noted that Mount Tom rises from a hollow extending 100 feet or more below the supposed marine level. It cannot then be shown to rise from a platform of marine origin. Nor can wave-cut notches be observed in the field near the base of the mountain at the supposed marine level. All forms are of the normal subaerial type. Nowhere is there evidence of marine modification of subaerial forms.

If the considerations set forth on the preceding pages are valid, none of the profiles published by Barrell demonstrate the marine origin of forms in southern

New England. Since these profiles were selected by Barrell as the best among a larger number prepared by him, it must be concluded that the evidence offered in support of marine terracing in southern New England is far from convincing.

AN ALTERNATIVE METHOD OF VIEWING THE SURFACE

It may be urged that terraces would be visible if some better method of representing the upland surface were available. Such a method has been devised and applied to New England by Professor Douglas Johnson. This is the method of "multiple projected profiles," based on the construction of a large number of closely spaced projected profiles of belts of very limited width. Each profile shows the high points in a narrow zone, viewed from any direction the investigator finds convenient. After the profiles are drawn, they are transferred to stiff cardboard, cut out to show the relief, and then mounted on standards at intervals corresponding to the width of the zone. By this method a three-dimensional picture of the upland is made available.

Multiple projected profiles and the picture they present to the eye are almost entirely free from subjective influences. No particular orientation of the profiles is required, for, while a direction of view at right angles to the geologic structure or to the trend of terraces offers certain advantages, the final result, being in any case three dimensional, will reveal terraces if such exist, regardless of the direction selected. While individual profiles are being constructed, the projection of points is done in a purely mechanical manner and with no hypothesis in mind. There are few chances for error in construction or for omission of significant points. If occasional errors are committed, they are of minor importance, because the determination of forms present does not depend on a single line, as may be the case with a composite projected profile. Each profile of a multiple projected series is automatically checked by others on either side of it.

The great difficulty with multiple projected profiles is their cost in time, labor, and money. The writer has been spared this cost because, many years ago, Professor Johnson began experimenting with various kinds of profiles in order to discover the particular type, scales, and zoning best calculated to render an effective picture of the New England Upland. In the light of these studies and with the aid of grants from the Columbia University Fund for Research, Professor Johnson prepared two sets of profiles, each covering all of New England south of Vermont and New Hampshire. One set, trending north-south, was prepared by projecting parallel zones of terrain each 2 miles wide (Fig. 8). The other set, trending east-west, projects parallel zones each 1 mile wide (Fig. 9). These multiple projected profiles were placed at the writer's disposal.

Both sets of profiles have been studied by the writer, special attention being paid to the Western Upland, where the supposed marine terraces are considered by Barrell to be best preserved. This examination shows that, when the profiles are viewed in the same direction as that used in the construction of Barrell's composite projected profile, breaks in slope corresponding to those selected by Barrell can be seen. But when the multiple projected profiles are viewed from different directions and from different elevations, no continuous breaks in slope and nothing resembling remnants of terrace treads can be traced across

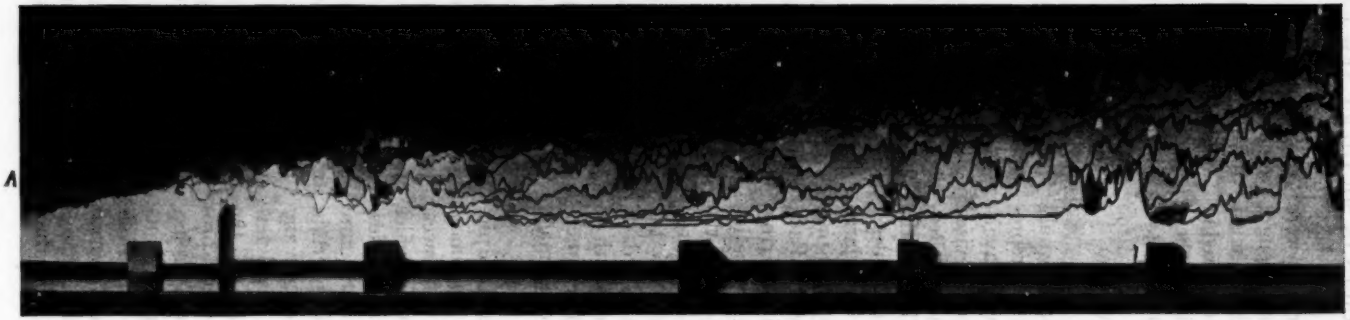

FIG. 8.—Multiple projected profiles (by Johnson), north-south set. Each profile covers a zone 2 miles wide. *ABCD*—Fall Zone; *EF*—inner margin of the Litchfield surface. Connecticut Lowland in foreground; Long Island Sound at left; Mount Greylock in right background.

the upland. The general impression gained from the multiple profiles is one not of terracing but of a subdued surface with irregular undulations. Many of the swells having linear extension trend oblique to Barrell's terrace trends, while many of the flatter areas do not slope seaward. The multiple projected profiles reveal many elements of form which do not appear on the composite projected type, but they fail to confirm the existence of marine terraces in New England. This led to Johnson's early conclusion that the supposed marine terraces were nonexistent.

FIG. 9.—Multiple projected profiles (by Johnson), east-west set of western Connecticut and Massachusetts north of the Fall Zone, looking north. *C*, Connecticut Lowland; *W*, Western Upland; *E*, Eastern Upland; *P*, Pomperaug Valley, Triassic; *M*, Mount Tom, Connecticut, hollow; *W*, Winsted, Connecticut, hollow; and *L*, Litchfield surface.

ANALYSIS OF FIELD EVIDENCE

After a critical study of topographic maps and composite projected and multiple projected profiles, the writer found that none of the evidence pointed to the existence of regional terraces of marine origin. But it would have been premature to discard the marine-terrace hypothesis simply from the study of topographic maps and their derived profiles. This is especially true where the maps themselves are known to be somewhat inaccurate representations of the topography. It was recognized that marine features might exist which were lost in the mapping.

To guard against this possibility, the writer prosecuted field work in the Western Upland and in portions of the Eastern Upland in an effort to find evidence of marine terracing. Most of the work was done near the lines drawn by Barrell to represent margins of the supposed terraces, but other areas of possible marine cliffs and benches were studied where maps indicated their possible pres-

ence. Some sixty "remnants" along Barrell's lines were investigated.

None of these areas showed marine features such as sea caves, wave-cut notches, stacks, or marine deposits. None of the supposed sea cliffs could be differentiated from other scarps not regarded as sea cliffs by Barrell, whether on the basis of steepness, height, length of base, levelness of base, obliquity to rock structure, or contact with benches. Benches in these areas are small, and many slope in the wrong direction or are on the landward side of hills. Supposed bench areas are, in many cases, separated from the nearest scarps by marked depressions, some in areas where no depression is indicated on the maps. In brief, extended field examination adds nothing to the evidence in favor of the existence of marine terrace remnants in New England.

CONCLUSIONS ON THE MARINE-TERRACE HYPOTHESIS

On the basis of map, profile, and field study the writer concludes that the supposed terrace remnants postulated by Barrell on the basis of his composite projected profile are, for the most part, insignificant features of the landscape which do not extend far across the upland and that, even where linear topographic inflections extend for some distance, their marine origin cannot be demonstrated. The marine levels predicated by Barrell and the restored shorelines based on them do not appear to rest on an adequate foundation of recognizable facts. All the forms observed find full and normal explanation on the basis of a continuous fluvial history. The geomorphic history postulated by Barrell, involving alternate marine and fluvial cycles, must accordingly be regarded as of doubtful validity.

FACETS OF THE NEW ENGLAND UPLAND

While valid evidence of a group of marine terraces on the New England Upland is lacking, one may distinguish a number of clearly developed "facets" of the upland surface, sloping at different angles. Some of the facets are separated from neighboring ones by steeper slopes, which may or may not be significant of the origin of the facets. The existence of such facets was early recognized by Douglas Johnson[24] from his study of multiple projected profiles. Examination of Barrell's composite projected profile (Fig. 2) indicates that to the north of the point *M* a mountain group rises abruptly far above the adjacent upland level, perhaps as a monadnock mass surmounting the surrounding peneplain. Between *M* and *L* the culminating hills of the dissected upland are strongly undulating, with no definite indication of terrace forms. If terraces ever did exist in this area, they have been so cut to pieces by stream erosion that they cannot now be distinguished from irregular swells on the sloping peneplain. At *L* there is a decided steepening of slope, south of which the culminating hills extend, with only minor breaks in the more gentle regional slope, to the point *S*. While a few broad valleys in this sloping facet leave higher hills to the north rising above lower hills to the south, thus giving a crude suggestion of terracing at one or more points, no undoubted terraces exist. South of *S*, the regional slope is notably steeper; but indications of terraces, as admitted by Barrell, are even weaker than elsewhere. This more steeply sloping facet has long been recognized as the Fall Zone peneplain, which intersects the less steeply sloping upland peneplain (Schooley?) at *S*. The only clear indication of a regional terrace

[24] Pp. 131–32 of ftn. 8 (1929).

shown on Barrell's composite projected profile (Fig. 2) is the broad upland facet extending from *L* to *S*. It is a reasonably even surface of moderate slope, terminated landward and seaward by notably steeper slopes. It does not correspond to any of Barrell's supposed terraces, being a broader feature of great areal extent. The question of its origin will not be considered at this time.

The regional extent of Barrell's supposed marine terraces (Fig. 2) may be determined by extending the inner and outer margins of the supposed terraces across the upland. This may be done directly on topographic maps by plotting the hills which rise to the levels selected for the inner and outer terrace margins. The lines thus drawn should consistently be close together where they delimit the supposed terrace risers and notably farther apart where they delimit the supposed treads.

Using the terrace levels selected by Barrell, the writer has drawn lines representing the landward and seaward terrace boundaries for the Connecticut portion of the Western Upland, where the supposed terraces are most clearly indicated on the composite projected profile (Fig. 2). As shown in Figure 6, the lines are not consistently close together at the supposed risers, nor do they remain consistently far apart on the supposed treads. Instead, the lines wander irregularly over the upland. Such an analysis indicates that terraces, if present at all, are only locally developed and are separated by large areas where no indication of terracing is present. It thus appears that multiple terraces of regional extent do not exist at the elevations selected by Barrell, on the basis of his composite projected profile.

To guard against the possibility that regional terraces might exist and not show on a composite projected profile, the writer has used another method of exploring the upland for such terraces. This is to construct generalized contours at regular vertical intervals, so drawn as to eliminate the disturbing effects of stream dissection, and to examine these contour lines for indications of regional terracing. The generalized contours are drawn, starting at the first interval above sea-level, by joining those points on interstream areas which first reach the level being contoured. Although personal judgment must be used in determining the precise positions of the contours, the general positions are fixed by a large number of points for each line and hence may be accepted with some degree of confidence as showing the general form of the upland before dissection. The map thus prepared (Fig. 10) indicates that the method of construction is sound, since it shows the same major features as are observed on the multiple projected profiles. The map shows in a single illustration, easily reproduced, features which require for their appreciation several photographs of the profiles.

If regional terraces are present in the Western Upland, the generalized contours should show consistent bunching on the risers and wide spacing on the treads of any terraces present, provided that the contour interval is smaller than the differences in terrace elevations. Examination of the map indicates that consistent alternate bunching and wide spacing of the lines is not regionally developed. Local bunching may be observed, as, for example, southwest and northeast of Peekskill, where the upland surface descends more or less abruptly to the Triassic Basin and its northeastward extension, along the Ramapo fault-line scarp. Another scarp, trending north-south, west of the lower Housaton-

ic River and east of the New York boundary, appears to have been the southwestern side of a broad sag associated with the Housatonic River, the sag having been locally steepened by excavation of less resistant limestones. A third zone of bunching extends northeastward from a point some miles northeast of Bulls Bridge on the Housatonic River to the Farmington River. Other scarps are indicated in the northwestern portions of the upper Westfield and Deerfield River basins, where the scarps trend parallel to structure and may be explained by the excavation of weak rock on the basin side of the scarp. The only one of these

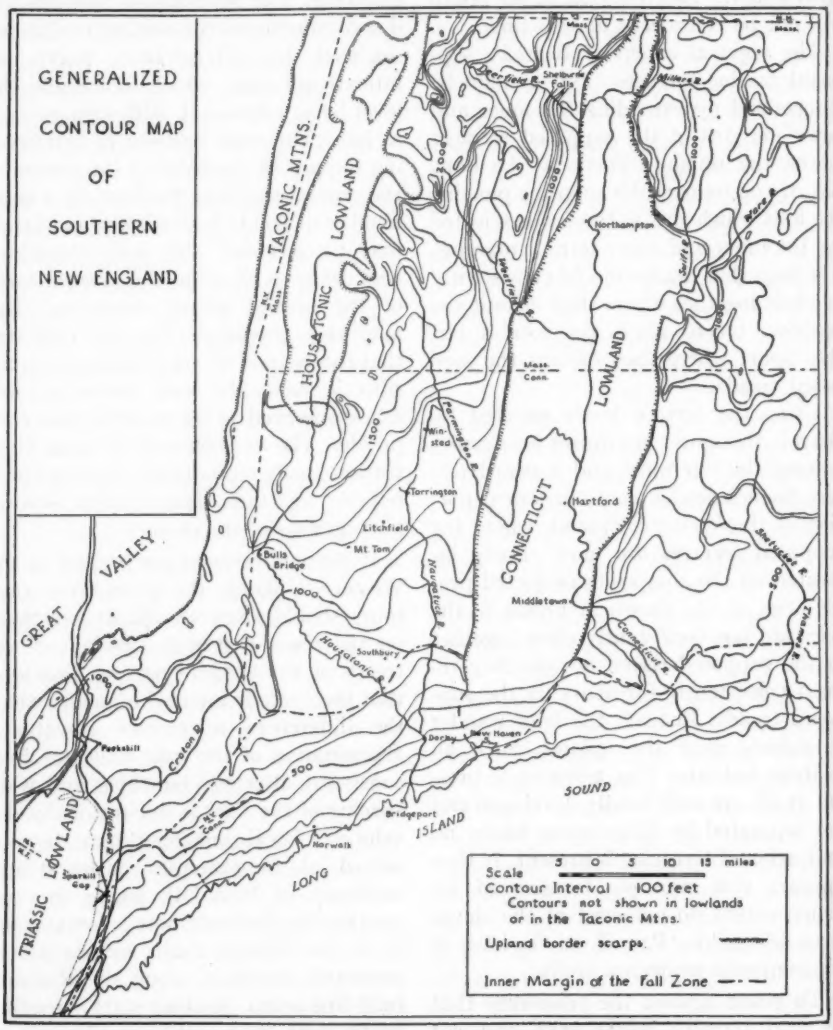

FIG. 10.—Generalized contour map of southern New England

zones of more closely spaced contours which seems unrelated to rock difference or known geologic structures is the one extending northeastward from Bulls Bridge to the Farmington Valley northeast of Winsted.

The relation of this local belt of steepening to the major facets of the Western Upland should be appreciated. Beginning at Long Island Sound, along the southern border of the Western Upland, a relatively steep slope, of 50 feet per mile, toward the south-southeast is maintained to about the 800-foot contour. For the next 20–30 miles northward the regional slope is almost due southeast and diminishes to 30 feet per mile. The facet of more gentle slope is gradually terminated northwestward by a narrower zone of relatively steep slope (60 feet per mile), shown on the map as the zone of bunched contours extending from the Housatonic River above Bulls Bridge and described above. To the northwest of this steeper zone, regional slopes generally diminish; but any exact determination of slope is rendered difficult by numerous local structurally controlled swells and hollows.

The writer concludes that the generalized contour map indicates a single surface or facet which with some show of reason might be called a "regional terrace." This is the surface sloping southeast at 30 feet per mile and terminated landward and seaward by more steeply sloping surfaces. It is shown on Barrell's composite projected profile extending from *L* to *S* (Fig. 2). This poorly developed terrace will be called the "Litchfield surface," from its best development in Litchfield County, Connecticut. The origin of the steeper zone, or "riser," terminating the Litchfield surface at the northwest is not clear; but Johnson[25] has suggested that such inflections of the present surface may represent monoclinal warping of a buried peneplain from which the sedimentary cover was later stripped. This interesting suggestion might be applicable if there were any indication of such a sedimentary cover over the upland surface. Johnson has presented other evidence that a sedimentary cover did extend over this area but that it blanketed the Fall Zone peneplain, which has since been beveled in this area to form the present upland surface. It appears reasonable that such beveling would have removed any structural inflections developed on the Fall Zone peneplain.

Examination of Johnson's multiple projected profiles indicates that multiple regional terraces are not present on the New England Upland. A few broad changes in slope are present, corresponding to those suggested by the generalized contour map and described above. The same structurally controlled irregularities are discernible.

Thus, after utilizing various methods of studying the Western Upland, it appears necessary to conclude that multiple terraces of a regional nature do not exist. Similar study of the Eastern Upland leads to the same conclusion. The single regional terrace which does appear as a real feature is confined to the Western Upland and is but faintly differentiated from the rest of the surface. It also appears from these studies that the upland of southern New England consists of a few broad facets, as earlier noted by Johnson, the significance of which will be considered in a later paper.

CONCLUSIONS

The more prominent upland irregularities used by Barrell to support the marine-terrace hypothesis are closely re-

[25] Pp. 7–8 of ftn. 7, *Stream Sculpture* . . . . (1931).

lated to geological structure and rock composition. Similar irregularities not appearing at the supposed terrace levels are numerous and are related to the same causes. Such irregularities are fully explained as the product of weathering and fluvial erosion and are to be expected in a peneplaned area of complex structure and diverse rock types. They doubtless existed in subdued form before uplift and dissection of the peneplaned surface. They have been emphasized where dissection is deep and where differential lowering of closely adjacent surfaces has occurred.

In view of this reasonable and adequate explanation of the upland irregularities, they cannot be accepted as remnants of marine terraces unless marine modification of subaerial forms can be established. No convincing evidence of such modification has been offered.

The writer agrees with Bryan[26] and his co-workers that it is impossible to prove that the sea did not make repeated advances over this area, to cut marine terraces. But, if such terraces were ever formed, they were so insignificant that weathering and fluvial erosion have since effectively obscured them or later fluvial peneplanation has completely removed them. No valid evidence that such forms ever existed has been found.

Applying this conclusion to the larger picture of Appalachian geomorphology, it can be said that no barrier exists to the application of the hypothesis of regional superposition in the New England area. Further search is, however, indicated to discover more positive evidence in favor of this hypothesis. This, too, will be the subject of a later paper.

ACKNOWLEDGMENTS.—The study presented in the preceding pages was suggested by Professor Douglas Johnson and has profited from his continuous critical supervision. The writer is further indebted to the searching criticisms of the Seminar in Geomorphology at Columbia University and to the friendly encouragement of Professor Bertram T. Butler, of the City College of the College of the City of New York.

[26] Kirk Bryan; A. B. Cleaves; and H. T. U. Smith, "The Present Status of the Appalachian Problem," *Zeitschr. f. Geomorph.*, Vol. VII (1933), pp. 312–20.

SMALL-SCALE STRUCTURES IN THE COCONINO SANDSTONE OF NORTHERN ARIZONA

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ABSTRACT

Small-scale structures, including ripple marks, slump marks of two types, and rain patches, occur locally on the surfaces of steeply dipping laminae in the eolian Coconino sandstone. These surface features are described and analyzed. Comparisons are made between them and similar structures observed in the modern dunes of the Navajo country. Most of these structures were reproduced experimentally in a wind tunnel and sand box, where controlled conditions made possible a determination of factors involved.

INTRODUCTION

The Permian Coconino sandstone of northern Arizona, which is a highly cross-laminated deposit of clean, well-sorted quartz sand, generally considered to be of eolian origin, locally contains an abundance of ripple marks and other minor structures and, in some places, great numbers of fossil footprints. A desire to determine accurately the environment in which these features were formed has prompted an examination of comparable structures among modern dunes in the Navajo Indian Reservation and the conducting of a series of experiments, the results of which are presented in this paper.

Shortly after the conclusion of the first season of investigation the definitive work of R. A. Bagnold[1] on the physics of blown sand and desert dunes became available to the writer and was of inestimable value in completing the studies. The painstaking experiments conducted by Bagnold made unnecessary a further search for many facts required in obtaining a satisfactory explanation of various features involved. Certain of the experiments that had a bearing on the study of small-scale structures in the Coconino have been repeated at the laboratory of the Museum; additional ones have been made where more information seemed desirable.

TYPE OF DUNES

Evidence of the eolian origin of the Coconino sandstone has been presented in papers by the writer[2] and by Parry Reiche[3] and will not be repeated here. Recognition of the type of dune, however, is essential to a full understanding of the ripple marks and other minor structures forming the subject of this paper and therefore warrants discussion.

Among various dune classifications that have been proposed, those by J. T. Hack[4] and by Bagnold,[5] based on form, in so far as it reflects genesis, are considered here because of their simplicity and applicability. Hack recognizes three primary dune forms: (1) transverse (including barchan), (2) parabolic, and (3) longitudinal. He also refers to several special types, developed as a result of such obstacles as topographic irregularities.

[1] *The Physics of Blown Sand and Desert Dunes* (New York: William Morrow & Co., 1943).

[2] "The Coconino Sandstone—Its History and Origin," *Carnegie Inst. Wash. Pub. 440* (1933), pp. 112–14.

[3] "An Analysis of Cross-lamination: The Coconino Sandstone," *Jour. Geol.*, Vol. XLVI (1938), pp. 916–18.

[4] "Dunes of the Western Navajo Country," *Geog. Rev.*, Vol. XXXI, No. 2 (1941), pp. 240–41.

[5] Pp. 188–89 of ftn. 1 (1943).

Bagnold considers as true dunes only those that can exist independently of any fixed surface feature and lists two fundamental types: (1) barchan, crescentic, or transverse; and (2) longitudinal or seif. Other types of sand accumulation, caused directly by sand obstructions such as bushes, rocks, or cliffs, he refers to as "sand shadows" and "sand drifts." These include the parabolic dune of Hack, which results from anchorage by vegetation.

In the Coconino sandstone there are no indications, such as projections from an underlying surface, that the deposits, even at the base, represent sand accumulations controlled by topographic irregularities. Nor is there any evidence in the form of plant molds or bedding disturbed by roots to suggest that vegetation played a part, with resulting parabolic forms. Of the other principal dune types, it seems unlikely that the longitudinal dune is represented, for, as pointed out by Reiche,[6] such dunes develop in districts of slight accumulation, where the sand is chiefly in transport. Furthermore, structures typical of this type of dune, as described by Bagnold, have not been recognized in the Coconino sandstone.

What appear to be small crescentic or barchan dunes may be observed in various parts of the Coconino sandstone where exposures are suitable. The curving fronts illustrated in lamination planes and the extended wings with high-angle dips in divergent directions are very prominent locally. In this formation, however, most of the planes of erosion and sets of steeply dipping laminae appear to be on a far larger scale and, as pointed out by the writer,[7] probably were formed as transverse (straight-fronted) dunes—a type differing from the barchan largely in degree. In typical transverse dunes the scale is so great that plunging "anticlines" or "synclines" with arclike pattern in cross section are not easily recognizable. Instead, the long, gently dipping planes of erosion, and the thick series of steeply dipping laminae with constant direction are the conspicuous features. Most of the Coconino structures appear to be of this type rather than of the barchan variety.

SELECTIVE PRESERVATION OF LEE-SLOPE SEDIMENT

Sand-dune deposits preserved in the geologic column probably consist almost wholly of lee-slope material. This conclusion was reached by F. W. Shotton[8] on the basis of theoretical considerations, and the principle involved has been demonstrated and explained by Bagnold[9] through studies of modern dunes in the Libyan Desert. In general, deposits of the approach side are only temporary and sooner or later are moved over the crest, building new laminae to leeward. Exceptions, consisting of the relics of windward-slope deposits, are locally preserved, along with the dominant lee-side laminae, as pointed out by W. O. Thompson[10] and other investigators; but these windward-side deposits are usually relatively easy to recognize as such. In barchan and transverse dunes laminae of the lee-side dip at a high angle, approaching 32° or 33°, and in directions that are, in general, comparable to the dominant wind direction of the area. Windward-

[6] P. 911 of ftn. 3 (1938).

[7] "Structures in Modern Sediments Aid in Interpreting Ancient Rocks," *Carnegie Inst. Wash. Pub. 501* (1938), pp. 688–90.

[8] "The Lower Bunter Sandstone of North Worcestershire and East Shropshire," *Geol. Mag.*, Vol. LXXIV (1937), p. 544.

[9] Pp. 241–42 of ftn. 1 (1943).

[10] "Original Structures of Beaches, Bars and Dunes," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), pp. 747–50.

side deposits, on the other hand, dip in the opposite direction and at angles less than 12°.

Applying the preceding considerations to the problem of the Coconino sandstone, it is clear (1) that the lee-side deposits should in most cases be distinguishable from those formed to the windward through a consideration of the direction and the degree of dip and (2) that laminae formed on the windward-side should be relatively scarce in this formation. Reiche[11] in an analysis of the Coconino cross-lamination has demonstrated that this is the case. Out of many hundreds of readings of lamination dip and strike, a large majority were found to dip between 15° and 30° in a southerly direction. The few exceptions dipping opposite were low-angle surfaces and therefore have been interpreted as representing true windward-side deposits.

EVEN-SURFACED LAMINAE

In wind-deposited sand being accumulated through saltation there is a pronounced tendency, under most conditions, to develop ripple marks. Because of the bouncing process involved, initial surface irregularities are accentuated and mounds of sand pile up rhythmically beyond them. The results of this tendency are conspicuous on the windward surfaces of most dunes. Where flat, rather than rippled, surfaces have formed among such deposits, the cause, according to Bagnold,[12] may be (1) continuous, rapid deposition that precludes opportunity for sand-sorting; (2) increase in wind strength, causing the length of the ripple marks to increase to such an extent that they finally disappear; or (3) sand of irregular grading in which some grains are much larger than others and are too large to be moved by the available wind, thus tending to break up any orderly ripple advance.

In the Coconino sandstone most lamination surfaces are extremely smooth and even. An adequate explanation of this feature seems essential to an understanding of the formation. A few of the laminae dip with low angle in a direction opposite the normal and so are considered to be windward-side deposits. In these the lack of rippling is probably the result of very rapid accumulation, for, as explained by Shotton,[13] deposits of the windward side have a good chance of permanent preservation only where the wind is being furnished an excessive supply of sand. Such rapid deposition has been shown by him to be unfavorable to ripple development.

Most laminae in the Coconino appear to have formed on the lee sides of dunes and therefore must have rippleless surfaces for a reason fundamentally different from that applied to windward-side deposits. Instead of being developed by the saltation of sand grains, these laminae are brought about largely by mass sliding or avalanching of sand down the steep lee slopes, as pointed out by Bagnold;[14] hence there is normally no tendency toward ripple development.

The principle involved in lee-side deposition is demonstrated by an experiment suggested by Bagnold in which sieved sand, dyed a different color for each of three size grades, is used. A sample in which these three grades are well mixed is allowed to avalanche down the steep slope of a sand box. When the material settles at the angle of repose, it is clear from the appearance of color bands that each sand grade has separated out into a separate flat layer or lamina.

[11] Pp. 905–32 of ftn. 3 (1938).

[12] P. 153 of ftn. 1 (1943).

[13] P. 544 of ftn. 8 (1937).

[14] P. 239 of ftn. 1 (1943).

Only on the sides or wings of barchans where wind currents often cross the steep slopes is there more than an occasional opportunity for re-working lee-side deposits and developing ripple marks (Fig. 1). Thus, the general lack of ripple marks and of surface structures in the Coconino sandstone appears to be largely a function of selective preservation of certain portions of the dunes, in which, with minor exceptions, conditions of deposition are unfavorable for ripple development.

FIG. 1.—Wing of barchan dune, showing ripple surface and slump marks on lee side, Tuba, Arizona

RIPPLE MARKS

GENERAL FEATURES

Ripple marks are not abundant in the Coconino sandstone but locally are moderately numerous. Approximately fifty sets from localities near Seligman, north of Ashfork, and in Oak Creek Canyon, Arizona, were examined in connection with this study. Many of the specimens, unfortunately, were not *in situ*, having been discovered in slabs of sandstone quarried for use as paving stone; but enough sets were located and examined in the field to determine their original positions with respect to the cross-laminated layers. On all specimens studied, a record was made of the height of the ripple crests, distance between crests, the ripple index (defined as the wave length divided by the amplitude), the degree of parallelism of individual ripples, and the amount of rounding of the crests.

Coconino ripple marks are all of one general type. Analyzing the results of examination, five features are found to be characteristic. First, they have a large ripple index, the lowest of those measured being seventeen, and most of them ranging well above this figure. Sec-

ond, all specimens found *in situ* have crests trending up and down the surfaces of sloping laminae and in no case normal to the dip. Third, the ripple crests are definitely rounded, as illustrated in every specimen examined. Fourth, there is a concentration of coarser sand grains on or about the crests in many specimens. Fifth, the crests and troughs within each set are remarkably straight and parallel, showing little change of direction even on large surfaces where exposures are continuous for 3 or more feet.

RIPPLE LENGTH

The length (distance between crests) of most ripple marks in the Coconino sandstone is between 100 and 150 mm., although exceptions are not rare. The largest ripple mark to be examined, a specimen from near Ash Fork, Arizona, is 302 mm. in length. Two other specimens measured only 75 and 85 mm., respectively.

According to E. M. Kindle,[15] "the size or amplitude of wind ripple mark varies but little with variation of wind velocity . . . . the principal factor controlling the slight amount of variation which is shown by the amplitude, appears to be the coarseness of the sand." This conclusion, based on general observations, apparently is incorrect. Bagnold[16] describes in detail the lengthening of ripple marks as a result of increased wind velocity, independent of changes in grain size and sorting. Furthermore, this relationship has been demonstrated repeatedly during the present investigation under controlled conditions of a wind tunnel where grain size could be kept constant and wind velocity changed as desired.

[15] "Recent and Fossil Ripple-Mark," *Can. Dept. Mines, Geol. Surv. Mus. Bull. 25* (1917), p. 12.

[16] P. 151 of ftn. 1 (1943).

The variations in wave length recorded for ripple marks in the Coconino sandstone probably represent differences in wind velocity. Grain size and degree of sorting are too similar in the samples studied to account for any large differences in ripple length such as are represented by the extremes noted above.

RIPPLE INDEX

High ripple index (above 15) is considered by Kindle[17] to be "the most striking characteristic of wind-made ripple mark," and studies by numerous other geologists have established the validity of using this feature in distinguishing between wind- and water-formed ripple marks. Bagnold[18] has shown that the index of wind ripple marks is controlled by the degree of sorting of the sand, very uniform grains tending to give only very low ripples and hence high indices. In using a single grade of sand (0.19–0.27 mm.) he found that "the ratio of height to wave length was usually 1 to 70, and never more than 1 to 30." Similar experiments conducted by the writer gave the results shown in Table 1.

TABLE 1

	Average Index
Mixed sand (0.5–1.0, 0.25–0.5, and 0.125–0.25 mm.)	16.0
Fine-grained sand only (0.125–0.25 mm.)	27.0
Medium-grained sand only (0.25–0.5 mm.)	26.0
Coarse-grained sand only (0.5–1.0 mm.)	29.0

Ripple-index determinations have been made for twenty-one specimens in the Coconino sandstone. Unfortunately, accurate measurements could not be made in other available specimens because ripple crests were weathered. The

[17] P. 12 of ftn. 15 (1917).

[18] Pp. 151–52 of ftn. 1 (1943).

indices determined range from 17 to 98, with fairly even distribution between these extremes. As the sand is quite well sorted, in general, the many high indices are not surprising.

RIPPLE ORIENTATION

A distinctive feature of ripple marks in the Coconino sandstone is that the crests and troughs extend up and down the lamination slopes, paralleling the direction of dip. Without exception, all specimens found *in situ* have shown such orientation. This characteristic is consistent with the theory that they were developed among lee-side deposits along the wings of barchan dunes.

Observations of modern barchans in the Navajo Indian Reservation indicate that gentle winds often move across the steep lee faces on the dune wings, parallel to the direction of extension, re-working the sand surfaces and developing ripple marks (Fig. 1). Under these conditions, ripple marks invariably strike in the direction of sand slope which is at right angles to that of wind movement. In contrast, when the wind approaches from other directions, rippleless laminae develop for the air currents then are diverted by the dune, causing sand accumulation by the normal sliding or avalanching method, as opposed to the saltation common to windward-side deposits.

Ripple marks on the windward sides of modern dunes show no constancy of orientation with respect to slope comparable to that found on barchan wings of the lee sides. Low-angle approach surfaces normally are covered with ripples in which crests and troughs strike in many directions and have no apparent relation to slope. Many crests show branching, curving, or irregular patterns.

Ripple marks formed by stream currents seldom, if ever, develop parallel to the direction of slope on steeply dipping beds. Movement of water downgrade must ordinarily cause any ripples that form to be at right angles to the direction of inclination.

Wave ripples, in contrast to those of water currents, have their orientation controlled by the direction of wave movement, independently of the configuration of the bottom. O. F. Evans[19] describes waves coming in toward the shore of a lake and moving nearly parallel to the axis of the subaqueous ridges, thus forming asymmetrical ripple marks with crests and troughs parallel to the direction of dip. Such ripple marks may resemble in attitude those of lee-side dune ripples, but their position relative to the sand slope will be a matter of coincidence varying with the relief of the sea floor, whereas the wind ripples are formed exclusively with the one attitude.

EXTENT AND PARALLELISM

Crests and troughs of ripple marks in the Coconino sandstone show a high degree of parallelism and a marked constancy of direction (Fig. 3). Although the maximum extent of most rippled surfaces in this formation is not determinable because of incomplete exposures, it is clear from available outcrops that ripple marks vary but little from top to bottom of the steeply dipping surfaces on which they are formed.

A regular, even, ripple pattern, such as that found in the Coconino sandstone, is a common feature of steeply sloping, lee-side deposits on modern barchan wings (Figs. 1 and 2) and, to a less extent, between the wings. It is readily explained as the result of ripple-forming

[19] "The Relation between the Size of Wave-formed Ripple Marks, Depth of Water, and the Size of the Generating Waves," *Jour. Sed. Petrol.*, Vol. XII (1942), p. 34.

winds which are able to approach such surfaces from one direction only. In contrast, ripple marks on the windward sides of dunes, where winds constantly shift direction, develop many bifurcations, variations in trend, and changes in size.

Many wave-formed ripple marks develop with a high degree of parallelism and straightness of crest and trough.

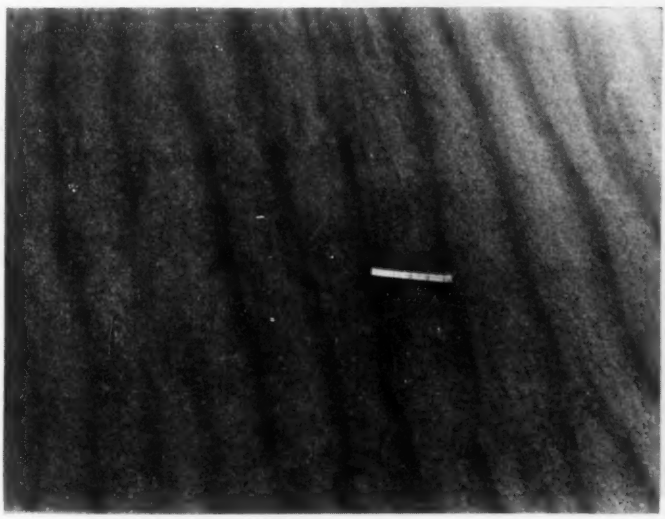

FIG. 2.—Stabilized wind-ripple marks on lee side of barchan dune near Tuba, Arizona

Such ripple marks form normal to the wave direction, irrespective of bottom topography and, therefore, are constant over wide areas. On the other hand, ripple marks formed by stream or other currents normally reflect great variation in direction and speed, and so they have extremely irregular patterns when considered over a large surface.

ROUNDED CRESTS

Ripple marks in the Coconino sandstone show a definite rounding of crests (Fig. 3). In some, the degree of rounding is so marked that it is almost equal to that of the troughs. In others, the contrast between gentle approach slopes and steep lee slopes is more apparent; yet surface rounding is still considerable.

A probable explanation for the high degree of rounding in ripple-mark crests in the Coconino sandstone has been obtained through examination of modern dune ripples in the Navajo Indian Reservation. It has been observed that freshly formed ripple marks are only moderately well rounded, whereas those that have been allowed to settle are flattened somewhat and have assumed a considerably more rounded form (Fig. 2). This suggests that those wind ripples that are permanently preserved in the geologic record are the ones that have had opportunity to stabilize between periods of sand accumulation and that for this reason rounding of crests is pronounced.

Well-rounded crests may also be found on ripple marks formed by water. In dis-

cussing wave ripples, O. F. Evans[20] states that "when a heavy sea is followed by a long period of gentle wave movement, a rounding and smoothing of the ripples occur. . . ." Thus, rounded crests are not necessarily indicative of eolian origin and are found among both water and wind-formed ripples where an alteration in form is developed during a period of stabilization.

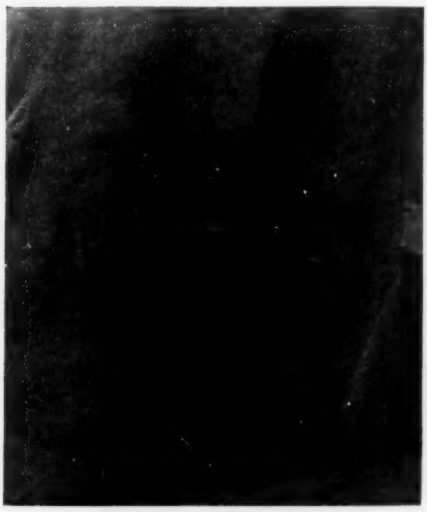

FIG. 3.—Ripple marks in Coconino sandstone near Ash Fork, Arizona.

GRAIN SORTING

Slabs of Coconino sandstone containing ripple marks have been cut and polished to show the distribution of sand grains in cross sections through the ripple series. In some samples no appreciable variations in grain size could be detected, the ripples apparently being formed in uniform, well-sorted sand. In others, grains of more than one grade size are present. Here the coarser grains form ripple crests, and the finer grains are in the troughs. Where rippling is absent and grains are of two grade sizes, the sand is separated into thin layers or laminae, consisting of an alternation of coarser and finer material.

The sorting of sand grains according to size in wind-ripple-mark specimens is a function of the process of deposition involved. The sand is piled up by saltation into a series of ridges in which the coarsest grains invariably collect at the crests, because, as explained by Bagnold,[21] they are less easily moved and, therefore, protect the crests, allowing them to rise into a region of stronger wind than would otherwise be possible. In contrast to this, sorting in the flat laminae, where rippling is absent, results from a different cause. Here the layers are developed by slumping or avalanching of sand grains (as opposed to saltation), a process in which the grains invariably become sorted according to grain size.

SLUMP MARKS

GENERAL

On the lee side of barchan or transverse dunes, especially in the steep middle portions, sand lies near the angle of repose with a surface that normally is smooth and flat and without ripple marks. This type of surface develops because saltating grains coming to rest on the upper part of the lee slope build up an oversteepened profile that is relieved periodically by avalanching. Such avalanching, as pointed out by Bagnold,[22] comes as a series of discontinuous jerks with successive miniature landslides

[20] "Effects of Change of Wave Size on the Size and Shape of Ripple Marks," *Jour. Sed. Petrol.*, Vol. XIII (1943), p. 38.

[21] P. 152 of ftn. 1 (1943).

[22] *Ibid.*, pp. 203 and 239; also, "The Transport of Sand by Wind," *Geog. Jour.*, Vol. LXXXIX (1937), p. 433.

forming to leeward each time the equilibrium of the steep slope is disturbed beyond a critical value. Although mass movements of this type result largely from overloading at the top of the lee slope, locally large-scale avalanches form from the weight of an animal walking along the top or as a result of undermining by a cross-current of wind. These avalanches cause the development on sand surfaces of a series of variable and irregular lines roughly parallel to the direction of slope and marking the borders of the sand mass that has slumped downward. For such lines the term "slump mark" is proposed.

Typical slump marks are preserved on slabs of Coconino sandstone in numerous localities. An attempt has been made through experimentation to determine the factors controlling their origin and the characteristics developed under varying conditions. The project was relatively simple, as it required only an artificial dune and an opportunity to observe and record features developed through disturbance of sand resting at the angle of repose. In order to note any effects of differences in grain size, the sand was first sieved into three grades (0.5–1.0, 0.25–0.5, and 0.125–0.25 mm.), each of which was dyed a distinctive color, following Bagnold's method. They were then thoroughly mixed and allowed to become sorted by natural processes during avalanching. In order to determine differences in slump marks due to degree of dampness, experiments made in dry sand were repeated in wet sand, damp sand, and wet sand that had dried.

SLUMP MARKS IN DRY SAND

In plan view, slump marks developed in dry sand show subparallel lines passing up and down the bedding slope and converging toward an apex near each end except where limited by the upper or lower margins of the sand surface. These lines that bound the area of slumping may be in the form of raised margins or of margins that are depressed, depending on local conditions. Likewise the area bounded by them may stand up as a low platform; or it may form a shallow, flat trough. Commonly both types are found in different parts of the same mass of slumped sand, the raised platform being in the lower portion, owing to the addition of sand that has slid down from above. If the sand is of several size grades, the coarser grains tend to separate out and slide down on top, forming the surface of the raised platform; but where sand is uniform-grained, the same surface features will develop, with texture playing no part.

Slump marks in dry sand show an infinite variety of form and detail. Only the simplest, basic type, as developed experimentally, has been described above, whereas in modern dunes compound forms with many nearly parallel lines commonly develop from a series of partially superimposed avalanches (Fig. 4). In some places, groups of overlapping tongues or funnels mark the bottoms of slumped sand patches; in other places, series of tiny, rounded, steplike structures develop because of the breaking-off of sand layers along lamination planes where contrasting grain size is involved. Several different types of dry-sand slump marks have been recognized on surfaces of the Coconino sandstone (Fig. 5).

Because avalanche surfaces characteristically develop on all parts of the lee sides of barchan and transverse dunes, the associated slump lines commonly serve as initial irregularities necessary to the development of ripple marks that form on the dune wings. In brief, the slump structures of a barchan center

commonly converge into well-formed ripple marks on the dune flanks.

SLUMP MARKS IN DAMPENED SAND

When dune sand is dampened, as by mist or dew (conditions simulated in experiments by using a fine spray), a crust, varying in thickness according to the depth of moisture penetration, is developed. Subsequent slumping causes this crust to break up into a jumble of irregular, thin patches of sand. Sand curls and crusty fragments form a confused mass. Similar results are obtained after the sand has dried out. This type of slump mark has not been recognized in any specimens of Coconino sandstone.

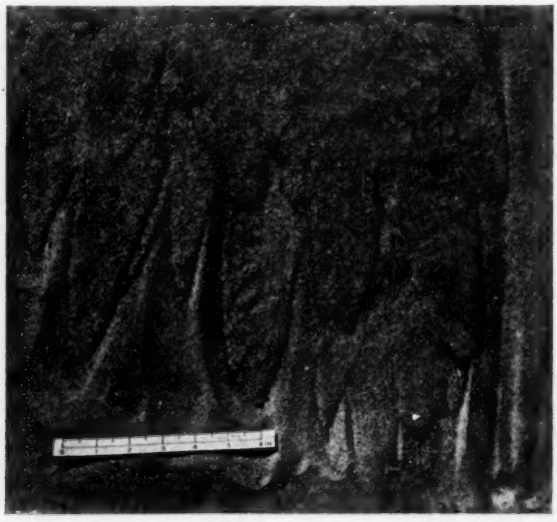

FIG. 4.—Slump marks in dry dune sand, Tuba, Arizona

SLUMP MARKS IN WETTED SAND

Dune sand that has been thoroughly wetted develops (either before or after drying out) a very characteristic type of slump mark when caused to avalanche by overweighting from above or by undermining due to crumbling away at the base. It forms a series of miniature steps, each a few millimeters high and with platforms dipping at an angle lower than that of the avalanche slope. The amount of each rise is dependent on the thickness of individual laminae, and these in turn are probably controlled primarily by the sorting process that plays such a prominent part in the forming of lee-side avalanche deposits. These structures are sharper and more pronounced than any comparable types developed in dry sand.

Wetted-sand slump marks were first reported from the Coconino sandstone by the writer[23] when he found an excellent specimen on the Grandview trail in Grand Canyon. A correct interpretation of this feature subsequently was suggested by Reiche[24] on the basis of observations that he had made on modern dunes in New Mexico. Other speci-

[23] P. 103 of ftn. 2 (1933).

[24] P. 918 of ftn. 3 (1938).

mens of Coconino sandstone illustrating wetted-sand slump marks have since been found by the writer near Seligman, Arizona (see Fig. 6).

RAIN PATCHES

The crater-like pits formed by raindrops in mud and other fine-grained materials are familiar to most geologists and have frequently been recorded in the literature. Impressions made by rain in sand, however, do not appear to have been recognized in many places in the geologic column. W. H. Twenhofel[25] refers to them briefly, stating that "the rims are not so sharp as those bordering impressions made in mud."

FIG. 5.—Slump marks in Coconino sandstone near Ash Fork, Arizona.

Examination of rain markings in dry dune sand shows that they are different from those formed in mud. Each raindrop, as it strikes the sand, develops a thin detached layer or shell, roughly circular but with irregular margins. The larger the pits, the more accentuated are these irregularities. Centers of the shells are depressed, and margins are very slightly raised above the general sand-level, as with rain pits formed in mud; but the detached character of the layer of sand gives it a distinctive form (Fig. 7). After drying, the circular shells normally remain firm and retain the same characteristics as when wet.

FIG. 6.—Slump marks in Coconino sandstone near Seligman, Arizona.

Rain patches formed on the steep, lee-side slopes of dunes are similar to those developed on horizontal surfaces except that the shells are oriented differently with respect to the lamination plane. In

[25] *Treatise on Sedimentation* (Baltimore: Williams & Wilkins, 1926), p. 490.

general, each circular shell tends to face upward or vertically, and on the steep surface this causes the downslope rim to be raised and the upslope rim to be depressed. Furthermore, only brief showers can leave such a record, for on the surface of a dune that is thoroughly wetted the shells lose coherence. Poorly preserved markings of this type have been noted in a few places in the Coconino sandstone.

this formation, are best explained as having been formed in dry sand. The few exceptions suggest sand that had been wetted as by a rain.

Even though these surface features appear to have had their origin in dry sand, they could scarcely have been permanently preserved in such a medium. Observations on dunes and other sand deposits indicate that except possibly under special conditions of marked tex-

FIG. 7.—Rain patches on steeply dipping surface of dry dune sand, Tuba, Arizona

CONDITIONS FOR PRESERVING STRUCTURES

Evidence, largely based on experimental work,[26] indicates that fossil footprints which are locally common in the Coconino sandstone probably were formed, for the most part, in dry sand. Likewise, as shown in the preceding discussion, most of the minor structures, such as ripple marks and slump marks in

tural change, parting planes do not develop when the sand is dry. In contrast, where the surface has been dampened, as by a dew or fog, a firm crust is developed and remains even after drying of the surface. Such dampening by dews is a common feature in desert areas and is considered to be a likely explanation for the permanent preservation of the minor structures where additional sand is drifting over the dune crests and burying the structure-bearing layers.

[26] McKee, "Tracks That Go Uphill," *Plateau*, Vol. XVI (1944), pp. 61–72.

SUMMARY

The Coconino sandstone is believed to consist of the deposits of barchan and transverse dunes, as suggested by the character of its cross-lamination. It appears to be made up very largely but not entirely of steeply dipping lee-slope deposits, in which the process of mass sliding or avalanching was dominant. This method of accumulation accounts for the preponderance of smooth, even-surfaced laminae in the formation. Locally, deposits appear to have been re-worked, as by winds passing along the lee sides of barchan wings; and in these places deposition was by saltation, with consequent ripple-mark development. On surfaces formed exclusively through the process of mass sliding the principal markings developed are marginal lines of individual avalanches, and related features here referred to as "slump marks." Rare shell-like patches, probably formed by rain drops, and reptilian footprints, nearly all of which go up hill, are other surface features found in these deposits.

ACKNOWLEDGMENTS.—Experimental work was undertaken in the laboratories of the Museum of Northern Arizona during the summers of 1943 and 1944. The writer was ably assisted in this project by Messrs. L. F. Brady and J. I. Snow and by Miss Betty Lou Decker, all of the Museum staff. The writer wishes also to acknowledge with thanks the constructive criticisms and suggestions offered by Drs. H. S. Colton, Parry, Reiche, and O. F. Evans after going over the manuscript.

GEOLOGISTS STARRED, 1903–43: WHERE EDUCATED, AGE

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ABSTRACT

The 272 geologists starred in the first seven editions of *American Men of Science* are listed, with date of birth and death (if dead); the place of their collegiate and doctoral training is given, arranged by institutions; trends in education and in institutional productivity are briefly discussed; and data on the age at starring are given.

INTRODUCTION

In the seven editions of *American Men of Science*[1] an attempt is made to sketch all living men and women who have made considerable contributions to the advancement of science in America. One thousand of the four thousand sketched in the first volume were selected (in 1903) as having made distinguished contributions, in the opinion of ten leaders in their science. The number of stars allotted to each science was roughly proportional to the number of recognized research workers in that science in 1903. The selection, after that of 1903, was partly by all previously starred workers in that science and partly by those recently nominated for starring.

During the period from 1903 to 1943, inclusive, 272 American geologists (including paleontologists, mineralogists, geophysicists, etc.) have been starred. The star implies either a large volume of good work or a considerable amount of especially original work. Although personality, position, and support also play a part in the voting, starring is a recognition which is less influenced by such secondary factors than is almost any other high honor received by scientists.

The star is a recognition which not only encourages and puts the starred men more fully on their mettle but attracts attention to their work. Starring also increases opportunities for further research, as grants and superior appointments are received comparatively readily by starred men. The various universities and other institutions employing starred scientists are placing increased value upon starring as a proof of individual merit and institutional strength. They not only attempt to retain and attract men already starred but hope to have other staff members not yet starred win this high honor; to this end they often increase facilities and otherwise encourage their more promising men.

Geology is advanced in numerous ways: by those who do high-class research, facilitate research, or aid in the effective presentation of research (editors, for example); by those who train future research men or who prepare the way for some sorts of geologic research (as, for example, topographers). It is also aided, of course, by those who, although their work is not especially original, nevertheless add substantial bits of geologic knowledge to the ever growing edifice.

Few can make major contributions but, unquestionably, he who encourages those who have done well, makes their work more widely appreciated, and stimulates others to higher efforts is accomplishing something worth while. Hence, studies such as this are mine

[1] Lancaster, Pa.: Science Press, 1906–44.

contributions to the advancement of geology.

In this study five chief things are undertaken. (1) All the 272 geologists starred in any of the seven starrings are listed alphabetically (in List 1), with the year of their birth and death (if dead) and the date when starred (indicated by numeral of the edition in which starring occurred: 1 for 1903, 2 for 1909, 3 for 1921, 4 for 1927, 5 for 1932, 6 for 1937, and 7 for 1943.) (2) The place of collegiate training (the Bachelor's degree) is given by institutions (in List 2). (The numeral after the name dates the starring and also renders unnecessary, in most instances, the given name, which may be found in the alphabetical list.) (3) Table 1, of the number of college alumni classified by starrings, makes more evident periodic changes in institutional productivity. (4) Similar institutional lists and Table 2 are given for doctorates conferred. Table 3 summarizes some data as to degrees held and place of training. (5) Finally, some data are given on the age at starring.

THE LIST

The list of 272 starred geologists is made up of 110 selected in 1903 and 25–30 first starred in each of the other six editions. The 110 of 1903 are listed, in the order of their distinction then, on pages 1273–74 of the fifth edition of *American Men of Science*, which volume also lists (pp. 1262–63) the 25 first starred in 1932. The full official lists of those starred in the other editions have not been published, except that for 1943, with one omission, but have been partly supplied to the present writer by Editor Cattell. A few men who at the time of their starring were more distinguished in some other field than geology are included, provided they are also known as geologists. For example, several paleontologists were starred as zoölogists or botanists; several mineralogists, as chemists or physicists. Any starred man long connected with the United States Geological Survey or otherwise widely known for his geologic work is included. For example, F. W. Clarke (*Data of Geochemistry*) was a distinguished chemist of the Geological Survey and certainly is properly included here, although he was not strictly a geologist. (If any of this list not reported as dead have died, information concerning the date of their death will be appreciated.)

LIST 1

GEOLOGISTS STARRED, 1903–43

	Born	Died	Edition Starred
Alden, William C.	9-27-71		*3
Anderson, Charles A.	6-6-02		*7
Antevs, Ernst	11-20-88		*5
Arnold, Ralph	4-14-75		*2
Ashley, George H.	8-9-66		*2
Atwood, Wallace W.	10-1-72		*3
Bain, H. Foster	11-2-71		*1
Balk, Robert	5-31-99		*6
Barrell, Joseph	12-15-69	1919	*2
Barton, Donald C.	6-29-89	1939	*5
Bascom, Florence R.D.	7-14-62	1945	*1
Bassler, Ray S.	7-22-78		*3
Bastin, Edson S.	12-10-78		*3
Bateman, Alan M.	1-6-89		*5
Bayley, William S.	11-10-61	1943	*2
Becker, George F.	1-5-47	1919	*1
Beecher, Charles E.	10-9-56	1904	*1
Behre, Charles H., Jr.	3-16-96		*6
Berkey, Charles P.	3-25-67		*3
Berry, Edward Wilbur	2-10-75		*3
Billings, Marland P.	3-11-02		*7
Blackwelder, Eliot	6-4-80		*3
Blake, Wm. Phipps	6-1-26	1910	*1
Bowen, Norman L.	6-21-87		*4
Bowie, William	5-6-72	1940	*4
Bowman, Isaiah	12-26-78		*3
Bradley, Wilmot H.	4-4-99		*6
Branner, John C.	7-4-50	1922	*1
Bretz, J Harlan	9-2-82		*6
Bridge, Josiah	7-17-90		*7
Brigham, A. P.	6-12-55	1932	*1
Brooks, Alfred H.	7-18-71	1924	*1
Brush, George J.	12-15-31	1912	*2
Bryan, Kirk	7-22-88		*5

LIST 1—*Continued*

	Born	Died	Edition Starred
Bucher, Walter H.	3-12-88		*5
Buckley, Ernest R.	9-3-72	1912	*1
Buddington, A. F.	11-29-90		*6
Burbank, W. S.	3-30-98		*7
Butler, Bert S.	3-30-79		*4
Butts, Charles	9-18-63		*4
Buwalda, John P.	12-16-86		*4
Calvin, Samuel	2-2-40	1911	*1
Campbell, Marius R.	9-30-58	1940	*1
Capps, Stephen R.	10-15-81		*5
Case, Ermine C.	9-11-71		*3
Chamberlin, Rollin T.	10-20-81		*3
Chamberlin, T. C.	9-25-43	1928	*1
Chaney, Ralph W.	8-24-90		*5
Clark, William B.	12-16-60	1917	*1
Clarke, Frank W.	3-19-47	1931	*1
Clarke, John Mason	4-15-57	1925	*1
Cloos, Ernst	5-17-98		*6
Cooke, C. Wythe	7-20-87		*6
Cooper, G. Arthur	2-9-02		*7
Croneis, Carey G.	3-14-01		*7
Crosby, William O.	1-14-50	1925	*1
Cross, Whitman	9-1-54		*1
Cushing, H. P.	10-10-60	1921	*3
Cushman, Joseph A.	1-31-81		*5
Dall, William H.	8-21-45	1927	*1
Daly, Reginald A.	5-19-71		*2
Dana, Edward S.	11-16-49	1935	*1
Darton, Nelson H.	12-17-65		*1
Davis, William Morris	2-12-50	1934	*1
Day, Arthur L.	10-30-69		*2
De Golyer, E. L.	10-9-86		*7
Derby, Orville A.	7-23-51	1915	*1
Diller, J. S.	8-27-50	1928	*1
Dodge, Richard E.	3-30-68		*1
Dunbar, Carl O.	1-1-91		*6
Dutton, Clarence E.	5-15-41	1912	*1
Eastman, Charles R.	6-5-68	1918	*1
Eldridge, George H.	12-25-54	1905	*1
Emerson, B. K.	12-20-43	1932	*1
Emmons, Samuel F.	3-29-41	1911	*1
Emmons, William H.	2-1-76		*3
Fairchild, Herman L.	4-29-50	1943	*1
Farrington, Oliver C.	10-9-64	1933	*1
Fenneman, Nevin M.	12-26-65		*3
Fenner, Clarence N.	7-19-70		*5
Ferguson, Henry G.	6-21-82		*5
Flint, Richard Foster	3-1-02		*7
Foerste, August F.	5-7-62	1936	*5
Fontaine, William M.	21-1-35	1913	*1
Foshag, William F.	3-17-94		*6
Gale, Hoyt Stoddard	12-9-76		*3
Gannett, Henry	8-24-46	1914	*1
Gardner, Julia	82		*1
Gilbert, Grove K.	5-6-43	1918	*1
Gilluly, James	6-24-96		*6
Gilmore, Charles W.	3-11-74		*5
Girty, George H.	12-30-69	1939	*3
Goldthwait, James W.	3-22-80		*4
Grabau, Amadeus W.	1-9-70		*1
Grant, U. S.	2-14-67	1932	*1
Graton, Louis C.	6-10-80		*3
Gregory, Herbert E.	10-16-69		*2
Gregory, William K.	5-19-76		*3
Griggs, D. T.	10-6-11		*7
Grout, Frank F.	1-24-80		*4
Gruner, John W.	7-12-90		*7
Gutenberg, Beno	6-4-89		*6
Hague, Arnold	12-3-40	1917	*1
Hall, Christopher W.	2-28-45	1911	*1
Harris, Gilbert D.	10-2-64		*1
Hatcher, John B.	10-11-61	1904	*1
Haworth, Erasmus	4-17-55	1932	*1
Hay, Oliver P.	5-22-46	1930	*2
Hayes, C. Willard	10-8-59	1916	*1
Heald, K. C.	3-14-88		*4
Heilprin, Angelo	3-31-53	1907	*1
Hess, Frank L.	9-4-71		*5
Hewett, Donnel F.	6-24-81		*4
Hilgard, Eugene W.	1-5-33	1916	*2
Hill, Robert T.	8-11-58	1941	*1
Hitchcock, Chas. H.	8-23-36	1919	*1
Hobbs, William H.	7-2-64		*1
Holland, William J.	8-16-48	1932	*1
Hollick, Arthur	2-6-57	1933	*1
Holmes, Joseph A.	11-23-59	1915	*1
Hotchkiss, William O.	9-17-78		*7
Hovey, Edmund O.	9-15-62	1924	*3
Huntington, Ellsworth	9-16-76		*3
Iddings, J. P.	1-21-57	1921	*1
Ingerson, F. Earl	10-28-06		*7
Irving, John D.	8-18-74	1918	*2
Jackson, Robert T.	7-13-01		*1
Jaggar, Thomas A.	1-24-71		*2
Johannsen, Albert	12-3-71		*3
Johnson, Douglas W.	11-30-78	1944	*3
Julien, Alexis A.	2-13-40	1919	*1
Kay, George F.	9-14-73	1943	*5
Kay, G. Marshall	11-10-04		*7
Keith, Arthur	9-30-64	1944	*1
Kemp, James F.	8-14-59	1926	*1
Kerr, Paul F.	1-12-97		*7
Keyes, Charles R.	12-24-64	1942	*1
Kindle, Edward M.	3-10-69	1940	*3
King, Philip B.	9-24-03		*7
Knopf, Adolph	12-2-82		*3
Knopf, Eleanora B. (Mrs. A.)	7-15-83		*6
Knowlton, Frank H.	9-2-60	1926	*1
Krumbein, W. C.	1-28-02		*7
Kummel, Henry P.	5-25-67		*1
Lahee, Frederic H.	7-27-84		*5
Lane, Alfred C.	1-29-63		*1
Larsen, Esper	3-14-79		*4
Lawson, Andrew C.	7-25-61		*1
Lee, Willis T.	12-24-64	1926	*3
Leighton, Morris M.	8-4-87		*5
Leith, Charles K.	1-20-75		*2

	Born	Died	Edition Starred
Leverett, Frank	3-10-59	1943	*1
Levorsen, A. I.	7-5-94		*7
Lindgren, Waldemar	2-14-60	1939	*1
Longwell, Chester R.	10-15-87		*5
Loomis, F. B.	11-22-73	1937	*4
Louderback, George D.	4-6-74		*3
Loughlin, Gerald F.	12-11-80		*4
Lovering, Thomas S.	5-12-96		*6
Lull, Richard Swann	11-6-67		*3
Macelwane, James B.	9-28-83		*6
McGee, W J	4-17-53	1912	*1
McLaughlin, Donald H.	12-15-91		*6
Mansfield, George R.	8-30-75		*4
Martin, Lawrence	2-14-80		*3
Mather, Kirtley F.	2-13-88		*4
Mathews, Edward B.	8-16-69	1944	*2
Mathes, Francois E.	3-16-74		*3
Matthew, W. D.	2-19-71	1930	*3
Mead, Warren Judson	8-5-83		*4
Meinzer, Oscar E.	11-28-76		*4
Mendenhall, Walter C.	2-20-71		*2
Merriam, John C.	10-20-69		*2
Merrill, Fred J. H.	4-30-61	1916	*1
Merrill, George P.	5-31-54	1929	*1
Mertie, J. B.	1-22-88		*7
Merwin, Herbert E.	2-20-78		*5
Miser, Hugh D.	12-18-84		*4
Moore, Raymond C.	2-20-92		*5
Newell, Frederick H.	3-5-62	1932	*1
Newhouse, W. W.	12-13-97		*7
Niles, William H.	5-18-38	1910	*1
Nolan, Thomas B.	5-21-01		*6
Osborn, Henry Fairfield	8-8-57	1935	*1
Palache, Charles	7-18-69		*2
Penfield, Samuel L.	1-16-56	1906	*1
Penrose, Richard A. F., Jr.	12-17-63	1931	*1
Pirsson, L. V.	11-3-60	1919	*1
Powers, Sidney	9-10-90	1932	*4
Prosser, Charles S.	3-24-60	1916	*1
Pumpelly, Raphael	9-8-37	1923	*1
Ransome, Frederick L.	12-2-68	1935	*1
Raymond, Percy Edward	5-30-79		*4
Reed, Ralph D.	4-21-89	1940	*6
Reeside, John B.	6-24-89		*5
Reid, Harry Fielding	5-18-59	1944	*1
Rice, William North	11-21-45	1928	*1
Rich, John L.	12-1-84		*6
Ries, Heinrich	4-30-71		*1
Rogers, Austin F.	8-15-77		*4
Ross, Clarence S.	9-20-80		*5
Rubey, William W.	12-19-98		*6
Ruedemann, Rudolph	10-16-64		*3
Russell, Israel C.	12-10-52	1906	*1
Safford, James M.	8-13-22	1907	*1
Sales, Reno H.	9-10-76		*7
Salisbury, Rollin D	8-17-58	1922	*1
Schairer, J. F.	4-13-04		*7
Schaller, Waldemar T.	8-3-82		*3
Schuchert, Charles	7-3-58	1942	*1
Scott, William B.	2-12-58		*1
Sellards, Elias H.	5-2-75		*5
Shaler, Nathaniel S.	2-21-41	1906	*1
Shand, S. James	10-29-82		*7
Shaw, Eugene W.	7-29-81	1935	*3
Shepard, Francis P.	5-10-97		*6
Short, M. N.	3-21-89		*7
Simpson, George G.	6-11-02		*7
Singewald, Joseph T., Jr.	9-25-84		*4
Smith, Eugene A.	10-27-41	1927	*1
Smith, George Otis	2-22-71	1944	*2
Smith, Jas. Perrin	11-27-64	1931	*1
Smyth, Henry L.	1-11-62	1944	*1
Spencer, Arthur Coe	9-27-71		*2
Spencer, J. W.	3-26-51	1921	*2
Springer, Frank	6-17-48	1927	*4
Spurr, Josiah E.	10-1-70		*1
Stanton, Timothy W.	9-21-60		*1
Stephenson, Lloyd W.	8-31-76		*4
Stevenson, John J.	10-10-41	1924	*1
Stock, Chester	1-28-92		*6
Stose, George W.	10-5-69		*4
Tarr, Ralph S.	1-15-64	1912	*1
Taylor, Frank B.	11-23-60	1938	*1
Thom, William Taylor, Jr.	6-9-91		*5
Todd, James E.	2-11-46	1922	*1
Tolman, Cyrus F.	6-2-73	1942	*3
Trask, Parker D.	5-7-99		*6
Trowbridge, Arthur C.	3-4-85		*6
Tunell, George	4-4-00		*7
Turner, H. W.	8-22-57	1937	*1
Twenhofel, William H.	4-16-75		*4
Ulrich, Edward O.	2-1-57	1944	*2
Upham, Warren	3-8-50	1934	*1
Van Hise, C. R.	5-29-57	1918	*1
Vaughan, T. Wayland	9-20-70		*1
Wadsworth, M. E.	5-6-47	1921	*1
Walcott, Charles D.	3-31-50	1927	*1
Ward, Lester Frank	6-18-41	1913	*1
Washington, Henry S.	1-15-67	1934	*1
Waters, A. C.	5-6-05		*7
Watson, Thomas L.	9-5-71	1924	*3
Weaver, C. E.	5-1-80		*7
Weed, Walter H.	5-1-62		*1
Weller, Stuart	12-26-70	1927	*1
Wentworth, Chester K.	5-7-91		*5
Wheeler, Homer Jay	9-2-61		*2
White, Charles A.	1-26-26	1910	*1
White, David	7-1-62	1935	*1
White, Israel C.	11-1-48	1927	*1
Whitfield, Robert P.	5-27-28	1910	*1
Wieland, George R.	1-24-65		*3
Williams, H. S.	3-6-47	1918	*1
Williams, Howel	10-12-98		*7
Willis, Bailey	5-31-57		*1
Williston, Samuel W.	7-10-52	1918	*1
Winchell, Alexander N.	3-2-74		*2
Winchell, Newton H.	12-17-39	1914	*1
Wolff, John E.	11-21-57	1940	*1

LIST 1—*Continued*

	Born	Died	Edition Starred
Woodring, Wendell P.	6-13-91		*5
Woodward, Robert S.	7-21-49	1924	*1
Woodworth, Jay B.	1-2-65	1925	*1
Wrather, William E.	1-20-83		*6
Wright, Frederick E.	10-16-77		*2

COLLEGIATE TRAINING

Grouped by undergraduate education, the starred geologists are found to have graduated from 81 American colleges or universities. Seven institutions graduated 9 or more—a total of 118, or nearly one-half of the total having American college degrees (Harvard, 38; Yale, 22; Cornell, 16; California, 12; Chicago, 12; Amherst, 9; and Columbia, 9). Eight institutions graduated from 3 to 7; 19 graduated 2 each; and 46 graduated 1 each (see List 2 and Table 1).

In the collegiate training of the older group (starred in 1903) Harvard, Yale, Cornell, and Amherst were pre-eminent, with 7–21 to each. Harvard also led in the 1932 group and tied for first place for the 1943 group. Yale ranked first for those starred in 1909 and tied for first for the 1943 group. Chicago ranked first for the group starred in 1921, tied for first for the 1937 and 1943 groups, and stood second for 1932. California tied for second place for the 1921 group and for first in the 1937 and 1943 groups. Cornell stood third in 1903 and tied for second in 1921 and for first in 1927. For the last three starrings combined, Chicago and Harvard tied for first; California and Yale for third; Denison, Hopkins, and Iowa for fifth. Of the 248 starred geologists who graduated from American colleges, many more than half had as an undergraduate at least one starred geologist as a teacher. It appears that most subsequently starred geologists chose their profession before graduating from college.

The most important influence in the

TABLE 1*

COLLEGIATE DEGREES TO STARRED GEOLOGISTS

Institution	Year in Which Starred								
	1903	1909	1921	1927	1932	1937	1943	Total	1932–43
Amherst	7	0	0	2	0	0	0	9	0
Beloit	3	0	1	1	0	0	0	5	0
California	1	1	3	2	0	3	2	12	5
Chicago	0	0	4	0	3	3	2	12	8
Columbia	5	1	2	0	1	0	0	9	1
Cornell	9	1	3	2	0	1	0	16	1
Denison	0	0	0	1	2	0	1	4	3
Harvard	21	1	2	1	5	1	2	38	8
Hopkins	1	1	0	1	1	1	1	6	3
Iowa	1	0	0	0	1	0	2	4	3
Kansas	1	0	1	1	1	1	0	5	2
Lehigh	0	1	0	2	0	0	0	3	0
Massachusetts Institute of Technology	3	0	1	2	0	0	1	7	1
Minnesota	1	1	1	1	0	1	1	6	2
Wisconsin	3	1	0	1	0	0	1	6	1
Yale	11	3	2	1	1	2	2	22	5

* Also, 2 each at Bryn Mawr, Cincinnati, Colby, Colgate, Cornell (Iowa), Illinois, Iowa State College, Maine, Massachusetts College, Michigan, Middlebury, Missouri, New Mexico, New York University, Oberlin, Princeton, Queen's, Stanford, Toronto, Washington (Seattle), and Wesleyan.

training of leaders in research clearly appears to be enthusiastic teachers of their science. Opportunities for employment undoubtedly are also highly significant, as are the ready availability of unsolved problems which are not too difficult for beginners. Without such problems, inspiring teachers have serious difficulty in developing productive followers. Without well-qualified teachers but with not too difficult research problems available, some scientists develop, largely self-taught. Nevertheless, even of the older starred geologists, each of a vast majority has named, on occasion, an enthusiastic teacher of geology as deserving great credit for having deeply interested him in the subject and started him on his scholarly career and for having provided vital parts of the background of training, objectives, and self-confidence which enabled him to attain a high level of research achievement. Often, of course, more than one teacher contributed notably to the inspiration of the embryo geologist.

Former teachers, now dead, who had two or more of their special undergraduate students later win stars include: Bascom (Bryn Mawr), Bayley (Colby, Illinois), Carney (Denison), T. C. Chamberlin (Beloit, Chicago), J. D. Dana (Yale), Davis (Harvard), Emerson (Amherst), Haworth (Kansas), Salisbury (Chicago), Shaler (Harvard), Tarr (Cornell), and H.S. Williams (Cornell, Yale). (Additions to this list of living men in this category, as well as deceased ones, will be welcomed.)

Although many colleges have given undergraduate work to starred geologists, only 3 were graduated from one of the numerous agricultural and engineering schools, and apparently none from the many state teachers or Catholic colleges.

LIST 2

Colleges from Which Starred Geologists Received the Bachelor's Degree

Amherst: Clark, 1; Clarke, J. M., 1; Cross, 1; Emerson, 1; Hitchcock, 1; Holland 1; Kemp, 1; Loomis, 4; Mansfield, 4

Beloit: Chamberlin, T. C., 1; Huntington, 3; Kummel, 1; Meinzer, 4; Salisbury 1

Bryn Mawr: Gardner, 6; Mrs. Knopf, 6

California: Buwalda, 4; Foshag, 6; Knopf, A., 3; Larsen, 4; Louderback, 3; McLaughlin, 6; Palache, 2; Ransome, 1; Schaller, 3; Short, 7; Stock, 6; Weaver, 7

Chicago: Atwood, 3; Behre, 6; Blackwelder, 3; Capps, 5; Chamberlin, R. T., 3; Chaney, 5; Flint, 7; Krumbein, 7; Tolman, 3; Trowbridge, 6; Wentworth, 5; Wrather, 6

Cincinnati: Bassler, 3; Bridge, 7

Colby: Mathews, 2; Smith, G. O., 2

Colgate: Brigham, 1; Cooper, 7

Columbia: Gregory, W., 3; Fenner, 5; Hollick, 1; Irving, 2; Matthew, 3; Merrill, 1; Ries, 1; Weed, 1; Willis, 1

Cornell: Ashley, 2; Branner, 1; Butler, 4; Cushing, 3; Derby, 1; Fairchild, 1; Graton, 3; Harris, 1; Hill, 1; Holmes, 1; Prosser, 1; Raymond, 4; Rich, 6; Martin, 3; Weller, 1; White, D., 1

Cornell College (Iowa): Alden, 3; Calvin, 1

Denison: Croneis, 7; Foerste, 5; Mather, 4; Moore, 5

Harvard: Barton, 5; Becker, 1; Billings, 7; Bowman, 3; Brooks, 1; Clarke, F. W., 1; Cushman, 5; Davis, 1; Diller, 1; Dodge, 1; Eastman, 1; Eldridge, 1; Emmons, 1; Ferguson, 5; Gale, 3; Gannett, 1; Goldthwait, 4; Jackson, 1; Jaggar, 2; Keith, 1; Lahee, 5; Lane, 1; Merwin, 5; Niles, 1; Penrose, 1; Shaler, 1; Shepard, 6; Smyth, 1; Spurr, 1; Tarr, 1; Tunell, 7; Vaughan, 1; Woodworth, 1; Wolff, 1

Johns Hopkins: Bayley, 2; Cooke, 6; Mertie, 7; Reeside, 5; Reid, 1; Singewald, 4

Illinois: Johannsen, 3; Ross, 5

Iowa: Kay, M., 7; Keyes, 1; King, 7; Leighton, 5

Iowa College: Leverett, 1; Springer, 4

Kansas: Case, 3; Dunbar, 6; Haworth, 1; Rogers, 4; Sellards, 5

Lehigh: Barrell, 2; Bowie, 4; Hewett, 4

Maine: Farrington, 1; Merrill, 1

MASSACHUSETTS INSTITUTE OF TECHNOLOGY: Burbank, 7; Crosby, 1; Grabau, 1; Loughlin, 4; Matthes, 3; Newell, 1; Stose, 4
MICHIGAN: Bastin, 3; Winchell, N., 1
MIDDLEBURY: Knowlton, 1; Hall, 1
MINNESOTA: Berkey, 3; Grant, 1; Grout, 4; Levorsen, 7; Lovering, 6; Winchell, A. N., 2
MISSOURI: Rubey, 6; Longwell, 5
NEW MEXICO: Bryan, 5; Johnson, 3
NEW YORK UNIVERSITY: Russell, 1; Stevenson, 1
OBERLIN: Hayes, 1; Todd, 1
PRINCETON: Osborn, 1; Scott, 1
QUEEN'S (Ont.): Bateman, 5; Bowen, 4
STANFORD: Arnold, 2; Hess, 5
TORONTO: Kay, G., 5; Lawson, 1
WASHINGTON (Seattle): Gilluly, 6; Waters, 7
WESLEYAN (Conn.): Rice, 1; Lee, 3
WISCONSIN: Bascom, 1; Buckley, 1; Hotchkiss, 7; Leith, 2; Mead, 4; Van Hise, 1
YALE: Blake, 1; Bradley, 6; Brush, 2; Bryan, 5; Dana, 1; Day, 2; Dutton, 1; Girty, 3; Gregory, H. E., 2; Hague, 1; Hatcher, 1; Hovey, 3; Iddings, 1; Nolan, 6; Penfield, 1; Pirsson, 1; Schairer, 7; Simpson, 7; Twenhofel, 4; Washington, 1; Williams, H. S., 1; Williston, 1

INSTITUTIONS GRADUATING ONE EACH

ALABAMA: Smith, E. A., 1; ALBION: Bretz, 6; ALBRIGHT: Woodring, 5; ALFRED: Butts, 4; ARKANSAS: Miser, 4; BOWDOIN: Wadsworth, 1; BROWN: Buddington, 6; CASE: Spencer, A. C., 2; CENTRAL (Mo.): Emmons, W., 3; COLORADO: Stanton, 1; COLORADO COLLEGE: Heald, 4; DARTMOUTH: Upham, 1; EUREKA (Ill.): Hay, 2; GEORGE WASHINGTON: Ward, 1; HEIDELBERG (Ohio): Fenneman, 3; HIRAM: Reed, 6; INDIANA: Kindle, 3; KANSAS STATE: Williston, 1; LENOX COLLEGE (Iowa): Merriam, 2; MASSACHUSETTS COLLEGE: Wheeler, 2; MOORES HILL (Ind.): Bain, 1; OCCIDENTAL: Kerr, 7; OHIO: Griggs, 7; OHIO (Athens): Safford, 1; OHIO NORTHERN: Mendenhall, 2; OHIO WESLEYAN: Shaw, 3; OKLAHOMA: De Golyer, 7; PENNSYLVANIA STATE COLLEGE: Wieland, 3; POMONA: Anderson, 7; ROCHESTER: Gilbert, 1; RUTGERS: Lull, 3; SCIO COLLEGE (Ohio): Stephenson, 4; SIMMONS: Ingerson, 7; ST. LOUIS: Macelwane, 6; TEXAS: Trask, 6; TRINITY: Bowie, 4; TULANE: Vaughan, 1; UNION: Julien, 1; VIRGINIA: Fontaine, 1; VIRGINIA STATE COLLEGE: Watson, 3; WASHINGTON AND LEE: Thom, 5; WEST VIRGINIA: White, I. C., 1; WILLIAMS; Powers, 4; WOFFORD (S.C.): Smith, J. P., 1; WORCESTER: Hobbs, 1; WYOMING: Gilmore, 5

DOCTORAL TRAINING

For their graduate work (List 3 and Table 2) most starred geologists attended relatively few universities. Very few took their doctorate at an American university which did not have two or more starred geologist professors. This implies that, with few exceptions, expert training is needed. Of the 1903 and 1909 groups, 14 obtained doctorates from Europe; but of the younger native geologists, only 1 (Bucher) did so. In recent years America has afforded at least as good advanced geological training as Europe, as well as more opportunities for well-qualified geologists. This helps to explain the immigration here of a number of capable geologists (6 among those starred during 1932–43).

Of the 188 starred geologists with regular doctorates (not honorary degrees), 102 received their degrees from four American universities (Yale 37, Chicago 23, Harvard 22, or Hopkins 20); and 24 received them in Europe. Of the remaining 62, 12 received their doctorate at California and 10 at Columbia. (For the complete list see List 3.) Of the recent starrings (1932–43), Yale conferred doctorates upon 15, Chicago 11, Harvard 11, California 6, Hopkins 6; no other university on more than 2 (Table 2).

Table 2 discloses interesting variations from time to time in institutional doctoral productivity. California stood low, or rather low, until 1937, when it tied for first place. Chicago led in 1921 and tied for first place in 1932 and 1937. Columbia and Cornell tied for third place in 1921 but stood low at the other starrings. Harvard stood high in 1903, 1927, 1932, and 1943. Hopkins stood

second in 1903 and fourth in 1932 and 1937. Yale led in 1903, 1927, 1943, and tied in first in 1932 and 1937.

The fluctuation in output of subsequently starred men correlates partly with the age of the leading teachers. Elderly men, despite perhaps earnest efforts strongly to stimulate their students to high achievement, are usually distinctly less successful in doing so than are men less removed from their students in age and achievement. When the gap in age and scholarly achievement between professor and student is large, the close fellowship which apparently is almost essential for effective stimulation can seldom obtain. Thus an enthusiastic, able instructor usually has far more influence on his students than the same individual has twenty or thirty years later, after he has become, perhaps, a world-renowned geologist.

Some mention of graduate work which did not lead to a doctorate is appropriate. A considerable number of starred geologists did not acquire an earned doctorate—55 per cent of those starred in 1903, about one-fifth of those of the next three starrings, and about one-tenth of those of the last three. Many of the older geologists had graduate work (without receiving a doctorate) in Germany or at Harvard. Of those starred during 1921–43 without a doctorate, 3 had graduate work at Chicago (Shaw, Tolman, Wrather), 2 at Yale (Heald, Rubey), 2 at Harvard (Gale, Matthes), and 1 each at Columbia (Sales), Cornell (Butler), and Massachusetts Institute of Technology (Burbank).

TABLE 2*

DOCTORATES TO GEOLOGISTS—SUMMARY

INSTITUTION	YEAR IN WHICH STARRED								
	1903	1909	1921	1927	1932	1937	1943	Total	1932–43
California	1	1	2	2	0	4	2	12	6
Chicago	2	0	8	2	5	4	2	23	11
Columbia	2	1	4	1	1	0	1	10	2
Cornell	1	0	4	0	0	1	0	6	1
George Washington	3	0	1	0	0	0	0	4	0
Harvard	6	2	0	3	5	1	5	22	11
Hopkins	7	4	1	2	3	2	1	20	6
Minnesota	0	0	1	0	0	1	1	3	2
Princeton	1	0	0	0	0	1	1	3	2
Stanford	0	2	0	0	0	1	1	4	2
Wisconsin	2	1	0	1	0	0	1	5	1
Yale	8	3	6	5	5	4	6	37	15
Foreign universities	8	6	2	1	2	3	2	24	7

* Also, 2 each at Massachusetts Institute of Technology (4, 7), New York University (1); 1 each at Bryn Mawr (6); Illinois (5); Iowa (5).

MOBILITY

There is a correlation between the number born in a region, state, or city and the number who had their college and graduate work there. However, detailed studies prove that starred geologists are highly mobile. Many did not attend the nearest good school; most of them went some hundreds of miles; and a few crossed the continent for their Bachelor's degrees, as did several for their doctorates.

A study of the approximate distance

from their birthplace to the college from which they graduated has been made for 205 geologists, with the following results: 5 native-American starred geologists graduated from a college more than 2,000 miles from their birthplace; 17 graduated from one 1,000–2,000 miles away; 30 from one 500–1,000 miles away; 34 from one 250–500 miles away; 46 from one 100–250 miles away; 47 from one 25–100 miles distant; and 26 from one within 25 miles of their birthplace.

For their graduate work, including formal study in European universities, 32 native-American starred geologists went more than 3,000 miles from their birthplace; 23 went 1,000–3,000 miles; 39 went 500–1,000 miles; 29 went 250–500 miles; 21 went 100–250 miles; 19 went 25–100 miles; while 15 received their graduate schooling within 25 miles of their birthplace. These latter were largely persons born in or near Boston, New York, Chicago, Baltimore, or San Francisco.

Despite the fact that the average starred geologist attended a college about 200 miles from his birthplace and had graduate work in a university more than 500 miles from his birthplace, nevertheless the large sections of the nation which were the birthplace of many subsequently starred geologists likewise trained many.

TABLE 3

SOME TRENDS BASED ON DECADE OF BIRTH

	Born before 1840*	Decade in which born						
		1840's*	1850's	1860's	1870's	1880's	1890's	1900's
Total number	25	27	39	54	54	43	27	14
No college degree	5	2	6	3	1	0	0	0
No graduate work	19	8	14	7	6	2	0	0
No doctorate	22	16	25	15	12	4	3	0
College degree from small college	8	13	8	14	16	9	5	4
College degree from a university	11	12	19	27	23	20	12	10
Chicago	0	0	0	0	1	4	3	2
Harvard	0	5	3	8	5	5	1	2
Hopkins	0	0	0	2	0	4	0	0
Yale	6	4	1	7	1	0	2	2
California	0	0	0	2	2	5	3	0
Other state universities	0	1	6	8	13	11	11	4
Doctorate from Europe	1	3	4	7	2	5	2	0
Doctorate from state universities	0	2	3	3	5	6	6	1
Doctorate from endowed universities	2	6	7	28	34	27	17	13
Chicago	0	0	0	2	5	7	4	2
Harvard	0	1	1	4	7	6	2	4
Hopkins	0	0	2	8	4	5	2	0
Yale	2	3	4	8	6	6	4	6

* Seventeen distinguished geologists who died before starring was done are included in this table. Seven were presidents of the Geological Society of America. Doubtless, all would have been starred had they lived to 1903. The 17 are: E. D. Cope, J. D. Dana, G. Dawson, J. Dawson, Jas. Hall, F. V. Hayden, T. S. Hunt, A. Hyatt, Jos. LeConte, J. Leidy, J. P. Lesley, O. C. Marsh, J. S. Newberry, Edw. Orton, J. W. Powell, G. H. Williams, and Alex Winchell.

SOME EDUCATIONAL TRENDS

Table 3 reveals some trends as to place and amount of schooling. A trend clearly evident is for more general academic training. Of the older starred geologists, a tenth were not college graduates; relatively few had doctorates. Of

those born since 1870, only 1 is not a college graduate, and only 7 born since 1879 do not have the doctorate.

Another trend is toward the increasing importance of the state universities in the training of geologists and the relative decline for the endowed colleges and universities, especially those of the Northeast. However, of the 14 born since 1899, only 4 got their college degrees from state universities (2 from Iowa), and only 1 his doctorate.

The declining importance of Europe in the doctoral training of starred geologists is notable. In brief, of those born before 1860 who had earned doctorates, Germany conferred them upon about one-third; of those born in the sixties, about one-sixth; of those born in the seventies, about one-twentieth. Of the native-American starred geologists born since 1888, not one received a doctorate in Europe.

LIST 3

UNIVERSITIES FROM WHICH STARRED GEOLOGISTS RECEIVED DOCTORATE

BRYN MAWR: Knopf, Mrs. A., 6;

CALIFORNIA: Anderson, 7; Buwalda, 4; Foshag, 6; Knopf, A., 3; Larsen, 4; Louderback, 3; Macelwane, 6; Palache, 2; Stock, 6; Trask, 6; Weaver, 7; Ransome, 1

CHICAGO: Alden, 3; Atwood, 3; Bain, 1; Bastin, 3; Behre, 6; Blackwelder, 3; Bretz, 6; Capps, 5; Case, 3; Chamberlin, R. T., 3; Chaney, 5; Emmons, 3; Fenneman, 3; Flint, 7; Kay, G., 5; Krumbein, 7; Kummel, 1; Leighton, 5; Mather, 4; Meinzer, 4; Moore, 5; Shepard, 6; Trowbridge, 6

COLUMBIA: Fenner, 5; Gregory, W., 3; Irving, 2; Johnson, 3; Kay, M., 7; Lull, 3; Matthew, 3; Merrill, 1; Ries, 1; Rogers, 4

CORNELL: Cushing, 3; Graton, 3; Martin, 3; Prosser, 1; Rich, 6; Watson, 3

GEORGE WASHINGTON: Bassler, 3; Hollick, 1; Knowlton, 1; Stanton, 1

HARVARD: Barton, 5; Billings, 7; Croneis, 7; Cushman, 5; Daly, 2; Foerste, 5; Goldthwait, 4; Griggs, 7; Jackson, 1; Jagger, 2; Lahee, 5; Lane, 1; McLaughlin, 6; Mansfield, 4; Merwin, 5; Penrose, 1; Powers, 4; Short, 7; Tunell, 7; Vaughan, 1; Wadsworth, 1; Wolff, 1

ILLINOIS: Ross, 5

IOWA: Wentworth, 5

JOHNS HOPKINS: Bascom, 1; Bayley, 2; Cooke, 6; Gardner, 6; Grant, 1; Haworth, 1; Hayes, 1; Hobbs, 1; Keyes, 1; Lee, 3; Mathews, 2; Mertie, 7; Reeside, 5; Reid, 1; Singewald, 4; Smith, G. O., 2; Spencer, A. C., 2; Stephenson, 4; Thom, 5; Woodring, 5

MASSACHUSETTS INSTITUTE OF TECHNOLOGY: Bowen, 4; Newhouse, 7

MINNESOTA: Berkey, 3; Gruner, 7; Lovering, 6

NEW YORK UNIVERSITY: Julien, 1; Stevenson, 1

PRINCETON: Bridge, 7; Buddington, 6; Osborn, 1

STANFORD: Arnold, 2; Ashley, 2; Kerr, 7; Reed, 6

WISCONSIN: Buckley, 1; Hotchkiss, 7; Leith, 2; Mead, 4; Van Hise, 1

YALE: Barrell, 2; Bateman, 5; Beecher, 1; Bowman, 3; Bradley, 6; Bryan, 5; Cooper, 7; Dana, 1; Day, 2; Dunbar, 6; Farrington, 1; Ferguson, 5; Gilluly, 6; Girty, 3; Gregory, H. E., 2; Grout, 4; Hewett, 4; Hovey, 3; Huntington, 3; Ingerson, 7; Kindle, 3; King, 7; Longwell, 5; Loughlin, 4; Nolan, 6; Raymond, 4; Rice, 1; Safford, 1; Schairer, 7; Sellards, 5; Simpson, 7; Twenhofel, 4; Waters, 7; Weller, 1; Wieland, 3; Williams, 1; Williston, 1

EUROPEAN UNIVERSITIES: Antevs, 5; Balk, 6; Becker, 1; Bucher, 5; Cloos, 6; Cross, 1; Eastman, 1; Emerson, 1; Gutenberg, 6; Hilgard, 2; Loomis, 4; Merriam, 2; Ruedemann, 3; Schaller, 3; Scott, 1; Shand, 7; Smith, E. A., 1; Smith, J. P., 1; Spencer, J. W., 2; Ulrich, 2; Washington, 1; Wheeler, 2; Williams, 7; Wright, 2

AGE WHEN STARRED

Table 4 presents facts as to age at starring. It discloses that the median age has varied from 40 to 49; a large share of the men were 45–55 when starred; 31 were past 60; and 48 were under 40 (of whom 23 were starred in 1903, 9 in 1909). Since 1909 only 2 men under 37 have been starred; but in 1903 and 1909, 12 men under 37 were starred.

Most of the men who were starred

under 35 years were born in the 1870's. Some of these had done enough work to win a star in 1903, when 110 men were starred and stars were easiest to get. This was because about a fourth of all of the geologists who had published several research papers were starred. Because of the sharp subsequent increase in the number of men who have done geological research, there have been in recent decades many more who have done considerable research; yet the number of stars is about constant. Most of those who had by 1903 held a doctorate in geology for more than a decade were starred, as well as many without a doctorate. In 1943, on the other hand, less than a twentieth of those who had held doctorates in geology for a decade were newly starred. One man of the 1903 starring was only 31 (Buckley), and three were 32 (Bain, Brooks, Ries). In 1909 Wright was starred at 32, and two at 34. None of the geologists born in the 1880's were starred in 1909; and, because no starring took place during the first World War, they had to wait twelve years for the next starring, until 1921, with the result that the youngest born in the 1880's were starred at 39. The geologists born in the 1890's did not need to wait so long for starring, as the next starring came in 1927. However, the youngest of the 1890–99 group was starred at 37—2 at 38, and 2 at 39. Only 13 geologists born after 1900 have yet been starred, at ages 32 (Griggs), 36, 37, 38, 39, 40, 41 (6), and 42.

Three of the 8 geologists starred while under 35 years before 1943 have already been elected presidents of the Geological Society of America, and a fourth is a member of the National Academy of Sciences. The recognition implied by early starring appears to have encouraged all but a few recipients to higher endeavors. The more honor is due, therefore, to the several geologists who, passed over at a previous starring and without the encouragement that this recognition affords, have had the persistence to continue their geologic studies until long after most men quit hard work and who won their stars at 65 or beyond—one at 79, another at 78, and others at 76, 70, 67, and 65 (2).

TABLE 4

AGE WHEN STARRED

Age	Year in Which Starred						
	1903	1909	1921	1927	1932	1937	1943
Median age	46	40	47	48	49	46	43
Percentage aged 45–55	33	18	56	56	40	56	25
Percentage under 45	40	65	32	32	36	44	50
Percentage over 55	27	17	12	12	24	0	14
Number past 60	19	3	1	2	2	0	4
Maximum age	81	78	61	79	70	55	67
Next oldest	77	76	59	65	61	55	65
Number under 40	23	9	2	3	0	6	5
Minimum age	31	32	39	37	40	36	32
Next youngest	32	34	39	39	41	38	38

CLARKSTON STAGE OF THE NORTHWEST PLEISTOCENE

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ABSTRACT

An episode of proglacial aggradation, here named the "Clarkston stage," is recorded in the Lewiston Basin region on the lower Snake River. Stream gravels accumulated to a depth of more than 400 feet in the Snake River canyon and in the lower portions of most tributary canyons. One or two tributary streams were ponded by the fill of the main canyon. The deposits are characterized by considerable cementation, weathering of basalt and granitic stones, and iron oxide stain. Two-story canyons were formed by cessation of erosion beneath the fill, prolonged lowering of slopes above, and later excavation of the fill. The Clarkston stage followed earlier Pleistocene deposition, deformation, and dissection but antedated the Wisconsin stage.

INTRODUCTION

The record of the latest Pleistocene of southeastern Washington has received considerable attention during the last two decades by workers who were primarily concerned with the origin of the channeled scablands and related features. Information on the stratigraphic aspects of Pleistocene history has been largely incidental to physiographic studies, and we have no clear understanding of Pleistocene chronology as a whole in that area.

Attempts to recognize a sequence of glacial and interglacial stages in the northeastern Washington area invaded by continental ice have not been successful, and it seems that a reliable Pleistocene chronology can best be worked out in southeastern Washington, where there is a considerable record of depositional and degradational episodes, deformation, renewed outpouring of lavas, and proglacial stages. Some of these events are recorded in the Lewiston Basin region about 100 miles above the mouth of the Snake River. The Asotin stage of canyon-cutting, apparently of early Pleistocene age, has been recognized there;[1] and stream and lake deposits of the Wisconsin stage are also present. It is now possible to recognize between these two extremes a new Pleistocene stage of proglacial aggradation which is named the "Clarkston stage." The primary purpose of this paper is to describe the stage in its type area centering at Clarkston, Washington. The stage is probably recorded by some of the early stream gravels, noted by earlier writers, in the region west of the Lewiston Basin; but the writer believes that correlation and tracing out of these and other deposits can be done best after a more complete Pleistocene chronology is established in critical areas.

[1] R. L. Lupher and Walter Warren, "The Asotin Stage of the Snake River Canyon near Lewiston, Idaho," *Jour. Geol.*, Vol. L (1942), pp. 866–81.

GENERAL GEOLOGIC SETTING

The known Clarkston deposits lie a short distance inside the eastern margin of the Columbia River basalts. In this region most of the major stream courses were established on an erosion surface of low relief prior to the Pleistocene. Early Pleistocene history is imperfectly known. The Ringold formation of south-central Washington apparently is the first sedimentary record. A critical question, upon which there is no general agreement, is that of the time relation of the Ringold formation to the diastrophic activity that initiated the present erosion cycle.

J. C. Merriam and J. P. Buwalda[2] believed that the Ringold was deposited in structural basins after the deformation. H. E. Culver[3] suggested that it was preceded by minor deformation and followed by major deformation, and Charles Warren[4] believes that deformation and deposition were largely contemporaneous. The writer believes that the Ringold, though early Pleistocene in age, is older than the major deformation because the sediments contain little erosional material from the basalts and extend into upland regions that have been trenched by the modern canyons. This conclusion leads to the thesis that the major deformation and dissection of the lava and, therefore, all lake and stream deposits of the present erosion cycle are of Pleistocene age.

The Ringold formation has not been certainly recognized in the vicinity of Lewiston Basin; a sedimentary deposit, largely eolian and commonly called the "Palouse soil" or "Palouse loess," lies upon the basalts in the Palouse Hills north of the basin, but little is known of its age or time range other than that the upper part is Pleistocene or Recent.

The major deformation of the lavas, presumably beginning early in the Pleistocene, produced the Columbia Basin, a major structural basin centering near the junction of the Snake and Columbia rivers and bordered by the Cascade, Blue, and Rocky mountains. In the Clarkston region (Fig. 1), well up on the eastern side of the basin, the lavas were warped and elevated so that streams of the present cycle carved many deep youthful canyons. Lewiston Basin at the junction of the Snake and Clearwater rivers is a minor structural and erosional depression about 18 miles long, 12 miles wide, and 2,000 feet deep (Fig. 2). The north side is a steep escarpment because the lavas, which are nearly horizontal beneath the plateau region to the north, bend down abruptly at angles of as much as 60°. The east-west axis of the syncline lies immediately south of Lewiston, close to the northern escarpment; the lavas rise southward at an average rate of about 3° to the Blue Mountains on the southwest and to Craig Mountain on the southeast. The structural closure of the asymmetric syncline is 1,700 feet, but the low central part has been eroded 300 feet deeper and somewhat widened by the Snake and Clearwater rivers, which debouch from deep canyons in the margins of the basins. Eight miles west of Lewiston the Snake leaves the basin through the northern escarpment, flowing at an altitude of 685 feet above the sea in a canyon 2,000 feet deep.

An early episode in the Pleistocene deformation and dissection of the lavas is recorded by the Asotin stage,[5] in which canyons across the growing Lewiston Basin syncline reached a maximum depth of 1,325 feet and then were nearly filled by lava flows, thus causing the streams to begin their work anew.

Most of the deformation and dissection came after the Asotin stage, and there is no known record of cessation of downcutting by streams until major canyons were nearly as deep as they are now; but before the end of the Pleistocene there came three episodes of proglacial deposition, each followed by dissection of the deposits and slight deep-

[2] "Age of Strata Referred to the Ellensburg Formation in the White Bluffs of the Columbia River," *Univ. Calif. Publ., Bull. Dept. Geol.*, Vol. X (1917), pp. 255–66.

[3] "Extensions of the Ringold Formation," *Northwest Science*, Vol. XI (193–), pp. 57–60.

[4] "Course of Columbia River in Southern Central Washington," *Amer. Jour. Sci.*, Vol. CCXXXIX (1941), pp. 221–22.

[5] Lupher and Warren, ftn. 1 (1942).

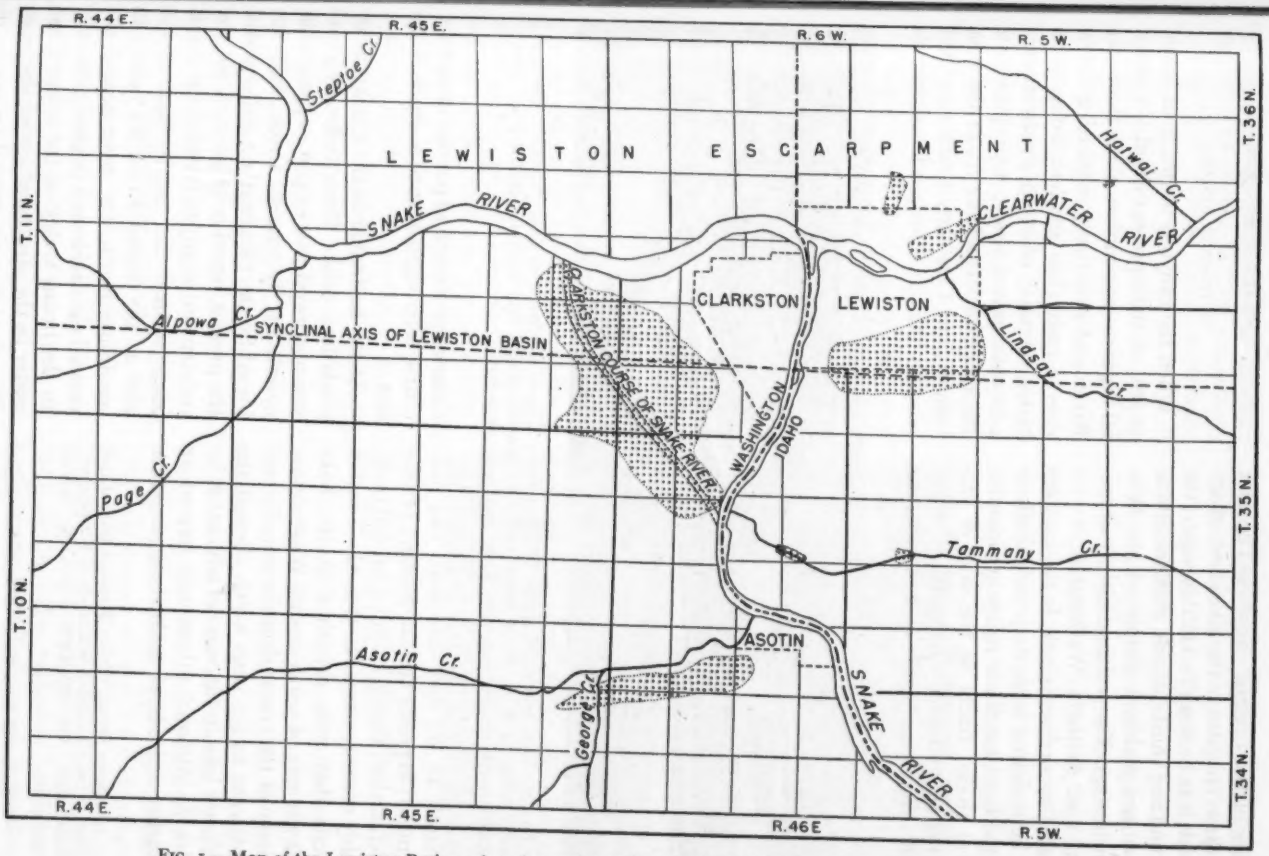

FIG. 1.—Map of the Lewiston Basin region. Approximate distribution of Clarkston fill remnants shown by stippling

ening of the original canyons. The first of these episodes is the Clarkston stage which is to be described in this paper; the second and third coincide with the much-discussed scabland history of the Wisconsin stage. The scabland history of central and southern Washington, as revealed by earlier writers, is too complex to be reviewed here; its principal effects in the Lewiston Basin region are found in local eroded tracts on the sides of canyons, discontinuous deposits of gravel and coarse sand,[6] and a more widespread mantle of silt and fine sand. The fine-grained deposits are the product of lake deposition; they are similar to, and probably contemporaneous with, the Touchet beds that were deposited in the Lake Lewis area of south-central Washington. Some of the coarse deposits were formed adjacent to ice jams which clogged the narrow lake in the manner advocated by Ira S. Allison;[7] others may record an earlier episode of normal aggradation.

CLARKSTON STAGE

OUTLINE OF HISTORY

When the canyons were cut to within 50 feet of their present depths, a gravel fill began to accumulate along the Snake River and eventually reached a thickness of more than 400 feet. Some tributaries, because of steep gradients and adequate gravel loads, kept pace with the rising surface of the fill in the main canyon; but Tammany Creek was ponded, and there is some evidence that the Clearwater River was ponded in its lower course after aggrading to a depth of 320 feet.

FIG. 2.—View southward across Lewiston Basin. City of Clarkston on right; Clarkston gravel fill in former course of Snake River trends northwest beneath plowed field beyond; post-Clarkston course of Snake River in center; Clearwater River and Lewiston on left.

At the beginning of the Clarkston aggradation, Snake River followed a canyon northwest from a point opposite the mouth of Tammany Creek and was joined by the Clearwater 4 miles west of the present junction (Fig. 1). A ridge of resistant intracanyon lavas of the Asotin stage formed the interstream divide; and as the Snake River fill neared its maximum depth, the river periodically crossed the divide and poured gravels into the broad valley of the lower Clearwater in the structural low of the basin. The river was superposed on one of the

[6] J Harlen Bretz, "Valley Deposits Immediately East of the Channeled Scablands of Washington," *Jour. Geol.*, Vol. XXXVII (1929), pp. 408–27, 505–9.

[7] "Flint's Fill Hypothesis of Scabland Origin," *Jour. Geol.*, Vol. XLIX (1941), pp. 54–73.

divide crossings during post-Clarkston dissection of the fill and cut a new canyon along its present course northward from Tammany Creek (Fig. 2).

The fill halted erosion in the deeper portion of the canyon, whereas normal lowering of slopes and stream gradients continued above the fill. Several rock terraces were cut at the highest level of the fill (Fig. 4). Subsequent erosion has removed most of the fill, and canyons now show a two-story effect: a rock-walled inner canyon below the original fill surface and more widely flaring upper slopes above the fill surface.

The cause of the Clarkston aggradation is unknown. However, it coincided, in some degree, with a glacial stage; and the common association of aggradation with proglacial conditions in other regions suggests that the Clarkston aggradation was induced by glaciation in the mountainous tracts drained by the Snake and Columbia rivers. The fill in Snake River canyon cannot be a valley-train deposit, in the sense of having been graded to a near-by glacier front. Presumably, the fill was caused either by increased load carried by tributary streams from widely distributed mountain glaciers in central Idaho and northeastern Oregon or, indirectly, by aggradation in the Columbia River valley at the mouth of the Snake. The diastrophic history of this part of the Pleistocene has not been elucidated; the possibility, therefore, of regional depression, or of faulting and warping west of Lewiston Basin, cannot be dismissed.

DESCRIPTION OF DEPOSITS

Stream deposits.—Most of the Clarkston fill is stream gravel in which are a few lenses of sand. The stream deposits are stained and cemented by iron oxide. Colors range mostly from light buff to brown, but some zones are so highly charged with oxide that they are orange or brick-red. Many pebbles are partly covered with a rough film of oxide. The degree of cementation is comparable to that of the Ringold formation of the earliest Pleistocene or to that of the Hood River conglomerate; stream gravels have stood with vertical and overhanging surfaces for many years without appreciable modification, and some of the sand deposits are sufficiently indurated to allow shaping into fairly durable hand samples.

FIG. 3.—Clarkston gravel in Clearwater valley, ½ mile south of Lewiston. Rough-surfaced pebbles near top are decomposed basalt.

The stones in the fill brought by the Snake and Clearwater rivers are almost wholly in the pebble and cobble range (Fig. 3). Stones in the 2–6-inch range make up the bulk of the fills; but small pebbles are numerous and, at their lower limit, grade into a matrix of coarse- to medium-grained arkosic sand. A number of lenses of arkosic sandstone, a few

inches to a few feet in thickness, have been seen in the Clearwater valley fill. Most pieces of boulder size are rolled blocks from near-by canyonsides; a few are roundstones; and some are ice-rafted erratics.

It is difficult to determine the abundance of erratics because (1) loose blocks of foreign rocks lying on eroded Clarkston fill cannot be distinguished from erratics carried during the Lake Lewis episode of the Wisconsin stage, and (2) most of the angular blocks buried in Clarkston fill are basalt and are to be suspected of local derivation. However, two unmistakable Clarkston erratics were visible in April, 1944, in a gravel pit on South Eighteenth Street at the southeast margin of Lewiston. These two blocks are angular; one, of granodiorite, is 51 inches in diameter, and another, of biotite schist, is 24 inches in diameter. They were inbedded in well-sorted pebble and cobble gravel. A similar block of granodiorite was seen in this pit in 1941, but it was subsequently removed. The nearest possible source for these rocks is at least 25 miles east of Lewiston Basin and their presence in the fine gravels of the Clarkston fill can be explained only by ice-rafting. Though only three erratics are certainly identified, the number is comparable to that found in a like number of exposures in other proglacial stream deposits of southeastern Washington when a similar restriction—large angular blocks of foreign rock *in situ*—is imposed.

The gravels contain Tertiary basalts and pre-Tertiary igneous and metamorphic rocks in nearly equal amounts, though local basalt rubble and rolled blocks predominate near canyon walls. The pre-Tertiary components, having traveled considerable distances from their sources in central Idaho and northeastern Oregon, are mostly well rounded; their shapes range from nearly spherical to elongate and flattened (Fig. 3). The basalt components, having come from distant as well as local sources, range from well rounded to angular. The pre-Tertiary rocks are in large part the resistant residues of prolonged abrasion of waste from a varied metamorphic and igneous terrane. Though the streams tap large exposures of granodiorite, the pebbles that reached the Lewiston Basin region are largely medium- and fine-grained acidic rocks that are probably from aplite and complementary dikes, pegmatite and vein quartz, and resistant porphyries. From the metamorphic terrane have come mostly quartzites and hard flinty greenstones, the latter derived from basaltic and andesitic lavas, tuffs, agglomerates, and intrusives. Pebble counts[8] show that Snake River gravels, of Pleistocene, and Recent ages, are characterized by abundant greenstone pebbles, whereas the Clearwater River gravels are characterized by much light-colored quartzite and granodiorite; the difference is sufficient to produce more somber colors in the Snake River fill. The gravels have undergone marked weathering, so that many of the basalt and granodiorite roundstones crumble soon after exposure (Fig. 3).

The Clarkston gravels in minor canyons around Lewiston Basin are composed of local basalt stones in a matrix of basalt waste, clay, and a small amount of arkosic sand derived from interbasalt sedimentary layers. In the canyon of Asotin Creek, a vigorous tributary of the Snake, the materials range from boulder gravel to fine gravel, and many stones are well rounded; in the canyon

[8] W. O. McKenzie, "Pebble Counts in the Lewiston Basin" (unpublished thesis, State College of Washington, 1942).

of Alpowa Creek, a less vigorous tributary, the stones are smaller, less rounded, and mixed with rubble and finer unsorted basalt waste; along Lindsay Creek, a small intermittent stream, the fill is largely angular rubble, stones rounded by spheroidal weathering, and finer material—all largely the product of mass wastage from near-by hillsides.

The Clarkston gravels are most reliably distinguished from Wisconsin gravels and other younger deposits by greater consolidation, by iron oxide colors, and by abundant decomposed roundstones. In contrast, the younger gravels are gray or dark-gray, less consolidated, and relatively unweathered. Petrologic composition is not a reliable distinction because Clarkston deposits have been extensively re-worked.

Lake deposits.—In the bed of Tammany Creek, about a mile above its mouth, a fine, blue-gray lake clay is exposed to a depth of a few feet. Yellowish-gray, well-stratified siltstones and sandstones, 20 feet thick, lie upon the clay. I. C. Russell[9] noted these deposits and rightly explained them as lake deposits formed in a ponded tributary of the Snake below the level of Snake River fill. However, the prominent bar of gravel and silt that Russell noted in the mouth of the canyon is of post-Clarkston age, and the original Clarkston gravel dam is exposed beneath the younger deposits only in the upper end of a narrow Recent trench carved by Tammany Creek.

Well-stratified brown sandstone is exposed also on the north side of Lewiston Basin, 1 mile northeast of the Clearwater dam, at an altitude of 325 feet above the river. The sandstone may be the record of sluggish water where Clearwater River flowed upon a broad fill surface in the middle of the Lewiston Basin, or it may be the result of ponding of the river by the Snake River fill. Ponding of the Clearwater is suggested also by a rubble deposit along the highway grade to the plateau north of Lewiston. It lies at altitudes of 1,050–1,250 feet A.T., or 340–540 feet above Clearwater River. The rubble contains angular and slightly rounded pieces of basalt that range from small pebble size to blocks 16 inches in diameter. The matrix, which makes up about half of the deposit, is dark gray-brown clay. The maximum thickness exposed is about 20 feet. The deposit lies upon basalt and is overlain by Touchet beds. Somewhat similar rubble is interbedded with Touchet silt near the bottom of the grade, and the entire deposit may be a marginal facies of the Touchet lake deposits. However, the deposits at the higher level show a degree of cementation and staining that is comparable to that of the Clarkston deposits.

The highest known occurrence of Clearwater River gravels of Clarkston age, in a fill remnant south of Lewiston, is 1,020 feet A.T.; this is 170 feet below the high level of near-by Snake River fill. It is possible that Clearwater River, like Tammany Creek, was ponded by more rapid growth of Snake River fill and that the sand and rubble at high altitudes on the north side of the basin accumulated at the margin of a lake.

DISTRIBUTION AND ALTITUDES OF REMNANTS

Snake River canyon and tributaries.—The remnants of Clarkston fill in the Snake and Clearwater valleys are largely obscured by a mantle of younger lake and stream deposits. Therefore, the stippled areas on the map (Fig. 1) do not show the distribution of Clarkston

[9] "Geology and Water Resources of Nez Perce County, Idaho," *U.S. Geol. Surv. Water Supply Paper 53* (1901), p.73.

deposits in detail but only the general areas in which those deposits are reliably indicated by partial exposure and topographic expression.

The largest remnant of Clarkston gravels lies in the abandoned segment of the Snake River canyon southwest of Clarkston. The fill surface is intact for a distance of a mile in the middle portion and is dissected at each end. Touchet lake silt, which once covered the entire remnant to a depth of several feet, has been removed from the steep surfaces of dissected portions. The upper surface of the fill is somewhat concave, lying at 1,160 feet A.T. in the middle and rising to 1,190 feet A.T. at the margins. The bottom of the former canyon is not clearly exposed but apparently is not more than 30 feet above the present surface of Snake River and, therefore, between 40 and 50 feet above the present bed of the river. These figures give a maximum vertical range of 450 feet from the highest marginal portions of the fill to the buried canyon bottom.

Most of the fill has been removed from the deep canyon below Lewiston Basin, though a few small remnants were noted in tributary gulches for a distance of 20 miles northwest of the basin. Remnants between Steptoe and Nisqually John creeks have flat tops that lie at 1,030 feet A.T., or 390 feet above present river-level. If the flats correspond to the highest level of the fill, a downstream slope of 12.8 feet per mile is indicated for the fill surface between Clarkston and Nisqually John Creek. The present gradient of the river, over the same reach, is 3.3 feet per mile.

Large remnants of the fill are present along lower Asotin Creek on the south side of Lewiston Basin and are well exposed in cuts along roads to the uplands south of the canyon. The upper surface of the fill is preserved by a veneer of stream gravel upon a prominent rock terrace (Fig. 4). The surface lies at 1,240 feet A.T. near the mouth of the canyon and rises to 1,335 A.T. 2.5 miles upstream, thus indicating a downstream slope of 38 feet per mile. The Clarkston lake sediments on lower Tammany Creek rise to 950 feet A.T. near the mouth of the creek and to 1,150 feet A.T. 3 miles upstream on a terrace that marks the former lake margin.

FIG. 4.—View westward up lower Asotin Creek, showing partly dissected rock terrace surfaced with Clarkston gravel. Note inner canyon below fill surface and subdued profiles above.

Clearwater valley and tributaries.—Prior to the Clarkston stage, Clearwater River flowed westward near the structural low of Lewiston Basin and joined the Snake 3.5 miles west of the present junction. The river had enlarged and deepened the downwarp, so that a structural and erosional depression, more than 3 miles wide and 6 miles long, lay below the upper limit of the near-by Snake River fill. There is no proof at present that this depression was filled with stream gravel to the high level of the Snake River fill.

The somewhat unusual nature of the elevated masses of Pleistocene sediments upon which the twin cities of Lewiston and Clarkston are built (Fig. 2) was noted and described by Bretz:

> The town and orchard tracts of Clarkston, Washington, are located on a sloping terrace-like fill composed of sand and gravel with prominent deltaic foresets. The deposit is a broad semimound resting against the southwest wall of the valley, its surface descending from the highest part roughly 50 feet per mile, down the valley, across the valley, and up the valley. Its upstream margin has been cliffed by undercutting of the Snake. This semimound is an impossible shape for a terrace top or a delta top, and the slopes are far too steep for either feature in a valley as broad as the Snake. There is no tributary drainage entering here from the higher land to the southwest, to which it might be referred as an alluvial-fan deposit.
>
> Pits in several places afford some idea of the nature of the material. Two different deposits underlie the tract: an older stained and weathered gravel beneath an unweathered younger deposit in which Columbia basalt constitutes about 80 per cent.[10]

The deposit beneath Lewiston has a closer resemblance to a terrace, especially when viewed from the west or north, where it has been undercut by the Snake and Clearwater rivers; but the top surface is noticeably rounded, with the high central point rising to an altitude of 850 feet A.T., or 140 feet above the adjacent river (Fig. 2). The top and undercut margins reveal only post-Clarkston deposits, but Clarkston gravels appear from beneath the younger deposits on the south side of the mound. South and southeast of Lewiston, a large dissected mass of gravel fill, partly obscured by a mantle of younger deposits, continues up the side of the basin to an altitude of 1,020 feet A.T. It seems probable that the Lewiston mound and the Clarkston semimound are largely erosional remnants of Clarkston gravel which are now largely hidden by younger surficial deposits.

The surficial deposits include partly cemented gray gravels intermediate in age between the Clarkston and the latest Pleistocene Touchet beds and scabland deposits. The intermediate gravels are well exposed along the north and northwest margin of the Lewiston mound. They resemble Clarkston deposits only in an appreciable degree of cementation, and they lack the iron oxide stain and weathered stones that characterize the Clarkston. Moreover, the gravels are of Snake River origin and were deposited near the bottom of the Clearwater valley after much of the original Clarkston fill had been removed. Similar gray gravels, 5–10 feet thick, lie between Clarkston remnants and the undulating mantle of Touchet lake silt at more than 1,000 feet A.T. on the south and southeast sides of Lewiston. These intermediate gravels are largely re-worked Clarkston gravels, probably left upon valley and canyon slopes during the dissection of Clarkston fill. Similar conditions may be repeated near Alpowa Creek and at several places in the canyon below Lewiston Basin, where alluvial deposits rise 50–135 feet above the

[10] Bretz, pp. 419–20 of ftn. 6 (1920).

river. Between Steptoe and Nisqually John creeks and at Davis Bar, near Almota, they form distinct terraces about 110 feet above the river; other deposits are of barlike or semimound aspect. The larger masses reach about the same altitude above the river as the top of the Lewiston mound, thus suggesting a considerably eroded post-Clarkston terrace. Exposures are shallow and reveal only gray, partly cemented gravel and later Pleistocene deposits; so it is not known whether the remnants represent an aggradational episode in the Clarkston-Touchet interval or a surface cut upon Clarkston fill and mantled by re-worked materials.

TOPOGRAPHIC EFFECTS ON COLUMBIA RIVER BASALTS

Two-story canyons.—The most pronounced effect of the Clarkston stage upon the regional topography was the development of two-story canyons. These canyons are remarkably similar to those formed by rejuvenation, but in this case they are related to aggradation. The alluvial fill of the Snake River and most of its tributaries eventually buried the lower portions of the youthful canyons to depths of more than 400 feet. The canyonsides probably were undercut by the streams during the upbuilding of the fill and perhaps also during its dissection; but the effect of the fill was primarily to bury and, in a sense, to fossilize the steep and rocky lower portions of the canyons for a long time. In the Clearwater canyon and its tributaries, alluvial fill, perhaps in combination with impounded water, produced the same result.

The fill must have remained at or near its maximum depth for a long time, because the canyon slopes above were considerably lowered by erosion and eventually blanketed by soil and vegetation. Likewise, the gradients of steams tributary to the Snake and Clearwater were progressively lowered upstream from the fill, which, as a rule, did not extend back more than 10 miles from the main river. Post-Clarkston dissection of the fill excavated the buried portions of the canyons and so revealed their steep rocky slopes in sharp contrast with the gentler, partly soil-covered slopes above.

The two-story character is prominent in the Snake River canyon northwest of Lewiston Basin and can be readily seen on the United States Geological Survey topographic map of the Pullman, Washington, quadrangle. The inner gorge does not owe its origin entirely to burial and exhumation, for it was locally eroded in its lower portion during the Wisconsin stage; and undercutting on the outsides of river bends, still in progress, has developed local precipitous slopes that rise even higher than the gorge. However, between the undercut slopes, even on the insides of river bends, are numerous steep slopes that rise from 350 to 400 feet above the present river and coincide at their upper limit with the highest level of Clarkston fill remnants. The canyonsides above the inner gorge and undercut slopes are noticeably less steep, and their contrast with the rocky cliffs of the inner gorge is heightened by a partial cover of soil and vegetation. A series of profiles, constructed from the topographic map of the Pullman quadrangle, shows an average slope of 32° on the inner gorge and 14° on the outer canyon.

In Asotin Creek canyon, south of Clarkston, a narrow inner gorge is 475 feet deep at the mouth of the canyon but decreases in depth upstream; and about 7 miles from the Snake River the

gorge ends, and the entire canyon has widely flaring soil-covered slopes. The stream gradient lowers abruptly as the canyon widens, and the knickpoint probably marks the upstream terminus of the fill. Similar conditions are encountered on Alpowa Creek. East of the basin the two-story character is well shown by the canyons of Clearwater River and Potlatch Creek; Cottonwood Creek canyon repeats the Asotin Creek–Alpowa Creek features.

Proof that the two-story canyons were caused by the Clarkston aggradation cannot rest entirely upon the coincidence of fill and inner canyon, for there is the possibility of a fortuitous coincidence of Clarkston fill surface with the knickpoints of a pre-Clarkston two-cycle valley formed by rejuvenation after an earlier valley stage. The best evidence for the aggradation thesis is the failure of inner gorges to continue upstream beyond the fill that lay in the lower portions of large canyons tributary to the Snake and Clearwater.

Rock terraces.—The "two-cycle" appearance of the canyon profiles is enhanced by rock terraces at the upper limit of the inner gorges. The terraces resemble the strath remnants of an early valley that are commonly preserved long after rejuvenation of a stream, but they are rock terraces cut by streams running at the upper level of Clarkston fill. The best example seen (Fig. 4) lies at the mouth of Asotin Creek canyon and extends upstream for 3 miles; it corresponds in altitude to the upper level of Clarkston fill and is partly covered by gravel. A similar but smaller terrace lies immediately west of Wawawai Creek in the Snake River canyon. Elsewhere along the Snake and Clearwater rivers the terraces are not large, but many spurs that come down the widely flaring outer canyon are beveled by horizontal or gently inclined surfaces at their junction with the inner gorge.

AGE

That the Clarkston stage coincided, to some degree, with a glacal stage of the Pleistocene is assured by large ice-rafted erratics in the stream deposits. It seems certain that it occurred long after the beginning of the Pleistocene but prior to the Wisconsin stage. It is not yet possible to estimate the position of the stage with reference to the Mississippi Valley sequence because of uncertainties regarding both number and ages of Northwest glacial stages; for the present it must be sufficient to locate the stage only with reference to local history.

The belief that the Clarkston stage occurred well within the Pleistocene is based upon the evidence that the major deformation, which initiated the present erosion cycle, came after the deposition of the early Pleistocene Ringold formation. Therefore, considerable time must be allotted for the Ringold deposition, the deformation and associated canyon-cutting, and, in the Lewiston Basin region, a repetition of canyon-cutting after lavas had nearly filled canyons of the Asotin stage. It is, perhaps, a late origin of the modern topography that has prevented recognition of early Pleistocene glacial stages in the Columbia Basin region.

An upper time limit for the Clarkston stage is set by the Touchet beds and little-consolidated scabland gravels and sands which mantle erosional remnants of Clarkston fill. It is generally agreed[11]

[11] Bretz, "The Age of the Spokane Glaciation," *Amer. Jour. Sci.*, 5th ser., Vol. VIII (1924), pp. 336–42; Richard F. Flint, "Origin of the Cheney-Palouse Scabland Tract, Washington," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), p. 468; Allison, p. 71 of ftn. 7 (1941).

that these younger deposits are of Wisconsin age. Allison[12] recognizes a twofold division of Wisconsin deposits near the mouth of Snake River; the older unit is represented by the high gravel terrace corresponding to the gravel dam[13] at the mouth of Palouse River, and the younger by Touchet beds and coarse scabland deposits of the Lake Lewis–ice-jam episode. He believes[14] that both units are younger than Clarkston deposits which are present in the same general region.

That the Clarkston deposits are older than Wisconsin is indicated also by their advanced degree of cementation, weathering, and iron oxide staining. Cementation of Clarkston deposits is comparable to that of early Pleistocene deposits, such as the Ringold formation, and many of the stream-worn cobbles and boulders are rotten to the core. In degree of weathering they resemble the Peshastin till described by Ben M. Page[15] as the first record of three successive Pleistocene glaciations in Wenatchee Valley, Washington. In contrast, the Wisconsin deposits seen by the writer and those described by Bretz,[16] Flint,[17] and Allison[18] are little consolidated, essentially unweathered, and lack a prominent oxide stain. Other evidences of antiquity are found in the length of time that would be required for the growth of the fill and the marked lowering of the outer canyon slopes while the fill remained in the canyon bottoms. Furthermore, the erosional interval between the Clarkston stage and the beginning of the Wisconsin deposition was of considerable magnitude. The fill, over 400 feet deep, was largely removed from Lewiston Basin and neighboring canyons; the Snake River cut a new course across the basalt ridge south of Lewiston and elsewhere cut its channel about 30 feet deeper into the basalt bedrock. Post-Wisconsin erosion is insignificant by comparison, for the thin mantle of Touchet lake silt is intact over much of the Lewiston Basin.

The conclusion indicated is that the Clarkston episode is a distinct proglacial stage in the middle part of the Pleistocene. The implication, of course, is that it is equivalent to either the Kansan or the Illinoian stage of the Mississippi Valley sequence, but judgment on that question must be deferred until further studies are made.

ACKNOWLEDGMENT.—The writer is indebted to Dr. Ira S. Allison, who read the manuscript of this paper and gave many helpful comments.

[12] Pp. 59–71 of ftn. 7 (1941).

[13] Flint, pp. 507–10 of ftn. 12 (1938).

[14] Personal communication (1944).

[15] "Multiple Alpine Glaciation in the Leavenworth Area, Washington," *Jour. Geol.*, Vol. XLVII (1939), pp. 785–815.

[16] Ftn. 6 (1929).

[17] Ftn. 11 (1938).

[18] Ftn. 7 (1941).

A MAJOR BURIED VALLEY IN EAST-CENTRAL ILLINOIS AND ITS REGIONAL RELATIONSHIPS[1]

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ABSTRACT

A large buried valley, tributary to the well-known bedrock valley along the Illinois River, has been traced eastward across central Illinois to the Indiana state line, and continuation into Indiana and beyond is indicated by well records and outcrop data. Detailed studies are confined largely to Illinois, and the valley is herein named "Mahomet Valley" after a locality in Champaign County, Illinois. Mahomet Valley is considered preglacial, as Kansan, Aftonian, and possibly Nebraskan deposits occur within the channel. After the advance of the Kansan glacier the valley probably ceased to function as a major drainage line; and by the end of Illinoian time the valley was so completely filled with drift that the Sangamon interglacial plain continued across it without interruption.

A new working hypothesis favored by the writer is proposed, namely, that Mahomet Valley represents the lower course of Teays River, a preglacial master-stream which probably had its source near the eastern scarp of the Blue Ridge in North Carolina; flowed westward across Ohio, northern Indiana, and central Illinois; and finally discharged into the Gulf Embayment through bedrock valleys now generally occupied by the present Illinois and Mississippi rivers.

INTRODUCTION

The geological studies made by the Worthen Survey of Illinois revealed that at several points in central Illinois the bedrock occurred at elevations much lower than at adjacent localities. The distribution of these low points led F. H. Bradley[2] to postulate that a preglacial valley extended southward from Lake Michigan through Kankakee and eastern Iroquois counties into Champaign County and thence northwestward under the city of Bloomington into the Illinois Valley in southern Tazewell County. It is now known that these low points lie within independent preglacial drainage systems.

Frank Leverett[3] confirmed the presence of low bedrock elevations in east-central Illinois and suggested possible relations to the preglacial courses of the Kaskaskia, Wabash, and Illinois rivers. In a regional summary in 1910, H. M. Clem[4] suggested the presence of a "spur" connecting Illinois and Wabash bedrock valleys; and in 1931, T. E. Savage[5] definitely related the preglacial drainage of the region to the Illinois bedrock valley. Within recent years L. E. Workman and George E. Ekblaw, of the Illinois State Geological Survey, in unpublished maps and cross sections outlined the eastern margin of the valley in Champaign County and made the first subsurface interpretation of the glacial deposits within the area.

The name "Mahomet" is herein proposed for the major bedrock valley crossing the area because near the village of Mahomet in western Champaign County

[1] Published with the permission of the chief of the Illinois Geological Survey, Urbana, Illinois

[2] "Geology of Kankakee and Iroquis Counties," in *Geology and Paleontology* ("Ill. Geol. Surv.," Vol. IV [1870]), pp. 226–40; "Geology of Champaign, Edgar and Ford Counties," *ibid.*, pp. 266–75.

[3] "The Preglacial Valleys of the Mississippi and Its Tributaries," *Jour. Geol.*, Vol. III (1895), pp. 744–57; "The Illinois Glacial Lobe," *U.S. Geol. Surv. Mono.*, Vol. XXXVIII (1899), pp. 654–64, 701–7.

[4] "The Preglacial Valleys of the Upper Mississippi and Its Eastern Tributaries," *Proc. Ind. Acad. Sci., 1910* (1911), pp. 335–52.

[5] "On the Geology of Champaign County," *Trans. Ill. Acad. Sci.*, Vol. XXIII (1931), pp. 444–45.

three wells penetrate bedrock at low elevations and determine the position of the deep part of the channel.

The present study is an outgrowth of a ground-water study of Pleistocene aquifers in central Illinois (Fig. 1), in which all available well records were examined, detailed studies were made of about seventy-five sets of well cuttings, and a contour map of the bedrock surface (Fig. 2) was compiled. Data for the bedrock-surface map of western Indiana were compiled from the literature and from well records provided by Wallace W. Hagan, formerly of the Indiana Division of Geology.

The thickness of the glacial drift in the area ranges from 0, where bedrock is exposed at the surface, to over 450 feet, where moraines of Wisconsin age cross deep bedrock valleys. Few water wells reach bedrock where the drift is over 200 feet thick,[6] whereas numerous wells reach it where the drift is thin. For this reason considerable detail of relief is usually shown on the bedrock uplands, but only the general outlines of the major valleys are revealed.

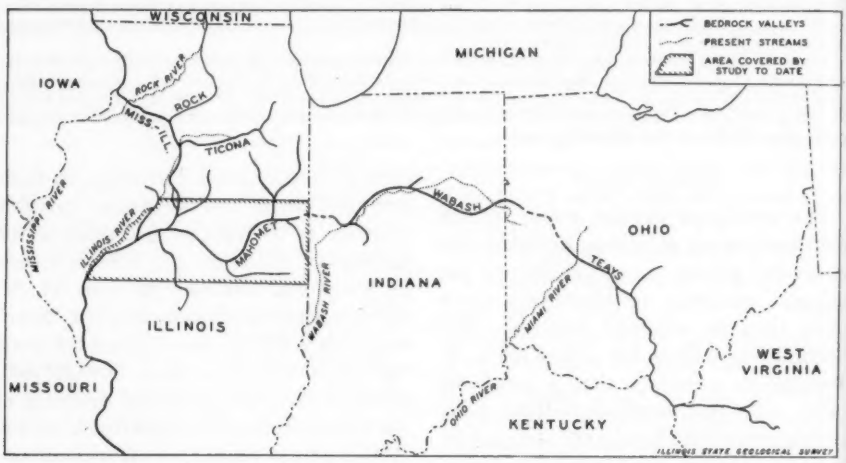

FIG. 1.—Map showing area studied in Illinois and proposed Teays drainage system. (Adapted in part after Fidlar, Tight, and Ver Steeg.)

DESCRIPTION

According to the present study, Mahomet Valley enters the state near the southeastern corner of Iroquois County and with a broad southward loop continues westward for 120 miles to enter the Illinois bedrock valley in southern Tazewell County (Fig. 2). Bedrock elevations along the valley are less than 400 feet above sea-level, or 200–300 feet lower than elevations on the adjoining bedrock uplands. The average depth of the valley appears to be about 200 feet, and in general the valley lies between the 300- and the 500-foot contours. The width of the inner portion of the valley lying below elevations of 450 feet is about 4 miles near the east state line, 5 miles in central Piatt County, and about 15 miles in DeWitt County. Although the valley-

[6] Mr. C. F. Stiegman, a water-well driller at Paxton, states that he has drilled wells along Mahomet Valley for twenty-five years without encountering bedrock in any of them.

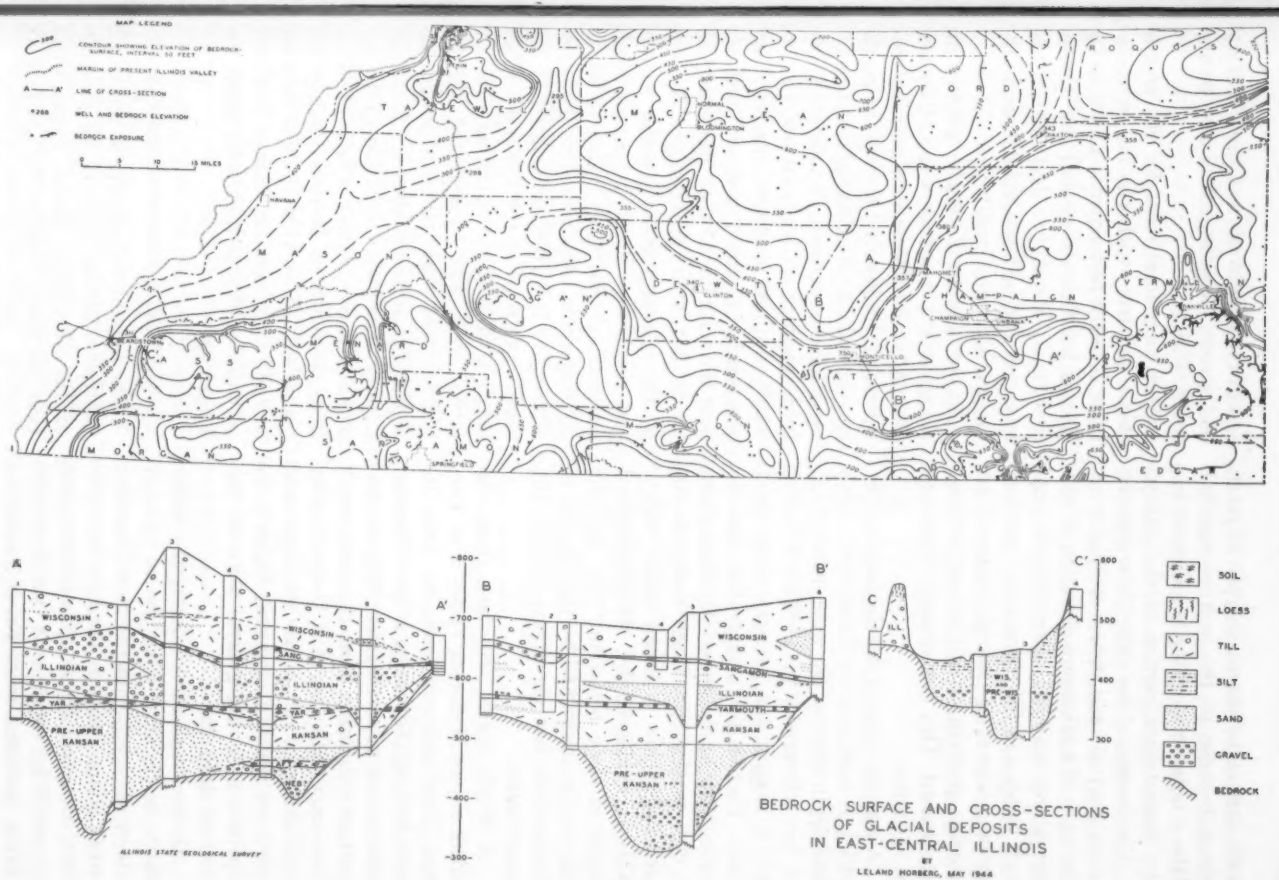
MAP LEGEND
CONTOUR SHOWING ELEVATION OF BEDROCK SURFACE, INTERVAL 50 FEET
MARGIN OF PRESENT ILLINOIS VALLEY
A — A' LINE OF CROSS-SECTION
*288 WELL AND BEDROCK ELEVATION
BEDROCK EXPOSURE
0 5 10 15 MILES
WISCONSIN
ILLINOIAN
YARMOUTH
KANSAN
PRE-UPPER KANSAN
SOIL
LOESS
TILL
SILT
SAND
GRAVEL
BEDROCK
ILLINOIS STATE GEOLOGICAL SURVEY
BEDROCK SURFACE AND CROSS-SECTIONS OF GLACIAL DEPOSITS IN EAST-CENTRAL ILLINOIS
BY
LELAND HORBERG, MAY 1944

FIG. 2

walls cannot be drawn sharply in most places because of the lack of detailed data, a notable widening is indicated for the downstream portion of the valley.

The descent of the valley floor appears to be gradual; and, when estimated on the basis of a minimum elevation of 280 feet above sea-level along Illinois bedrock valley and the elevation of 300 feet above sea-level at Oxford, Indiana,[7] an average gradient of 1.65 inches per mile is obtained. This is a descent of 20 feet in 145 miles.

A mature stage of development of the valley is indicated by its relative width and depth and by the wide distribution of low elevations in DeWitt County, which suggest the presence of a flood plain. There is also a suggestion that the valley may have been eroded during two cycles so that the inner valley is entrenched below a broad outer valley. This is evidenced by the pronounced break in slope below the 550- and the 500-foot contours and by the absence of comparable low elevations outside the inner valley.

A single major tributary from the north enters Mahomet Valley near Paxton. This valley appears to have its source along the margin of the Niagaran escarpment in northeastern Illinois. Important tributaries from the south enter Mahomet Valley north of Danville, west of Monticello, and in western Logan and northern Menard counties, which is in opposition to the general slope of the present drift plain.

Bedrock uplands bordering the valley range in elevation from 720 to 550 feet above sea-level, with the most extensive areas falling between the 550- and 600-foot contours. These uplands are parts of preglacial watersheds that separated River Mahomet from River Ticona[8] to the north, from upper Mississippi drainage to the northwest, and from Wabash and lower Mississippi drainage to the south (Fig. 1).

Maximum total relief for the area is about 460 feet, with the lowest elevations, 280–290 feet above sea-level, along Illinois bedrock valley and the highest elevations, about 720 feet above sea-level, on the bedrock upland in northeastern McLean County.

In the absence of closely spaced data along the upper course of the valley two alternative interpretations may be considered: (1) a low divide near the northern boundary of Champaign County may have separated Mahomet Valley from another valley east of Paxton, which drained eastward rather than westward; (2) there may be a divide near the state line so that Mahomet Valley did not extend into Indiana. By both of these interpretations major valleys end abruptly without important headwater tributaries, thus failing to satisfy physiographic requirements. The first alternative is further discounted by the northwest trend of the tributary valley north of Danville, indicating drainage to the west, and by a record showing bedrock less than 380 feet above sea-level in the northwest part of Champaign County. The major objection to the second alternative is the low bedrock elevations in southern Benton County, Indiana (Fig. 4). In view of these facts the writer's interpretation, shown in Figure 2, will be assumed in subsequent descriptions.

RELATION TO PRESENT TOPOGRAPHY

The present topography of the area is controlled almost entirely by moraines of the Wisconsin glacial stage, which bear no direct relation to the bedrock

[7] Leverett, p. 757 of ftn. 3 (1895).

[8] H. B. Willman, "Preglacial River Ticona," *Trans. Ill. Acad. Sci.*, Vol. XXXIII (1940), pp. 172–75.

topography and cross Mahomet Valley at various angles without change in trend or elevation. These moraines belong to the Tazewell substage, and in succession northeastward from the outermost are the Shelbyville, Cerro Gordo, Champaign, Bloomington, Normal, and Chatsworth.

The western part of the area lies west of the Wisconsin drift margin (Fig. 3) and includes uplands underlain by loess-covered Illinoian drift and a broad bottom land along the present Illinois River (Fig. 2). The lowland, which is a striking feature of the middle Illinois Valley, coincides with an extensive bedrock lowland developed at the confluence of the Mahomet and Illinois bedrock valleys and four important tributary bedrock valleys.

RELATION TO BEDROCK

Mahomet Valley cuts across regional structural trends and, from east to west, crosses the western Indiana syncline, the LaSalle uplift, and the northern part of the Illinois basin. The rocks underlying this area are largely nonresistant Pennsylvanian shales, although limestone and sandstone beds locally form thin units of greater resistance to erosion.

The major feature due to differential erosion is the bedrock lowland along the Illinois River and the related narrows at Beardstown (cross section *C–C′*, Fig. 2). The narrows resulted from entrenchment in more resistant Mississippian limestones, which are exposed along the river at this point; and the lowland may be attributed to lateral planation of weaker Pottsville and Carbondale strata upstream from this local base-level. Other features of the preglacial surface which locally appear to reflect bedrock lithology are: (1) the broad ridge in western Ford County may be due to Devonian-Silurian limestones along the LaSalle uplift; (2) the small upland in southwestern Vermilion County represents an outlier of LaSalle limestone; (3) the narrow ridge in north-central Douglas County is a reflection of Devonian-Silurian limestones along the crest of the LaSalle uplift; (4) the valley-wall in northern Menard and northwestern Logan counties may be partly the result of control by Pennsylvanian limestones above No. 6 coal.

DESCRIPTION OF THE VALLEY-FILL

Eleven units of Pleistocene deposits have been identified in the area:

11. Post-Shelbyville (Wisconsin) till and outwash
10. Shelbyville (Wisconsin) till
9. Sangamon soil and alluvium
8. Upper Illinoian till
7. Middle Illinoian sand and gravel
6. Lower Illinoian till
5. Yarmouth soil and alluvium
4. Kansan till
3. Kansan sand and gravel
2. Aftonian alluvium
1. Nebraskan (?) sand and gravel

Within this sequence significant unconformities occur at the base of the Kansan sand and at the bases of the Yarmouth and the Sangamon interglacial deposits. These unconformities are responsible for major variations in the succession below the Sangamon soil zone; the Wisconsin tills form a relatively regular unit, in which Shelbyville and post-Shelbyville divisions are usually recognizable. An outstanding feature of the pre-Wisconsin deposits is the dominance of water-laid silts, sands, and gravels within Mahomet Valley in contrast to glacial till, which is the dominant material along the margins of the valley and under the adjoining uplands (cross sections, *A–A′* and *B–B′*, Fig. 2).

RELATIONS OF THE SANGAMON AND THE YARMOUTH SOIL ZONES

The Sangamon plain below Wisconsin drift has been reconstructed for a part of the area on the basis of about 200 well records in which buried soil was either logged by the driller or was determined from sample cuttings (Fig. 3). Considering the minor errors possible in logging and in determining the location and elevation of wells, the close agreement of data-points for any given part of the map is noteworthy. The plain slopes gently away from the bedrock upland in McLean County and crosses Mahomet Valley without significant change in gradient. In Macon, Piatt, and western Champaign counties most of the elevations fall between 620 and 640 feet above sealevel. The surface has an average gradient of about 5 feet per mile and varies in elevation from 760 to 590 feet above sealevel. In northwest Champaign County a shallow sag in the plain lies approximately over Mahomet Valley, but elsewhere there is no coincidence with the bedrock surface. Upon this plain were spread the Wisconsin drift sheets and their moraines.

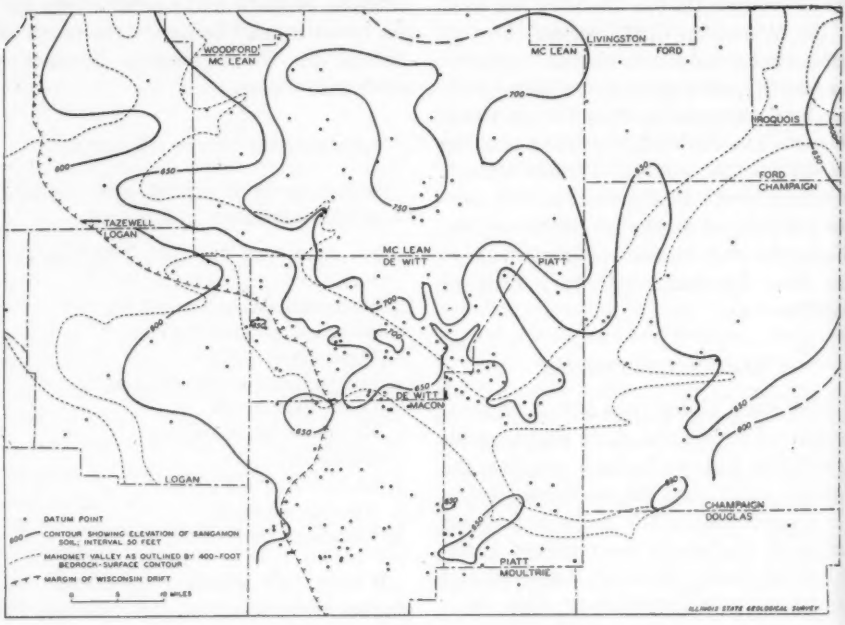

FIG. 3

The Yarmouth surface is not so well known as the Sangamon, but it appears to cross Mahomet Valley at fairly uniform elevations (cross sections *A–A′* and *B–B′*, Fig. 2). About 60 wells in the area covered by Figure 3 encounter the horizon and indicate that the undissected

plain was generally parallel with the Sangamon surface. Highest elevations occur over the bedrock upland in McLean County, and from that area the Yarmouth surface slopes outward in all directions. Elevations range from 670 to 514 feet above sea-level, most of them falling between 550 and 600 feet.

INTERPRETATION OF LOCAL DRAINAGE HISTORY

The oldest feature of the bedrock surface is represented by the upland surface, which crosses the structures of the area and slopes southwestward from elevations of about 600–500 feet above sea-level. The most extensive parts of this surface appear to lie between the 550- and the 600-foot contours. In the northern part of the area in McLean and eastern Iroquois counties higher portions of the upland rise to a uniform level of about 650 feet and have restricted summits at elevations over 700 feet. In northwestern Illinois a summit erosion surface, called the "Dodgeville peneplain,"[9] has been recognized. This surface slopes southward from an elevation of about 900 feet in the Driftless Area to an elevation of about 600 feet in the Starved Rock region in LaSalle County.[10] Bedrock valleys, eroded 200–300 feet below this upland, are pre-Kansan and probably preglacial in age. The elevation, slope, and dissection of the bedrock uplands in east-central Illinois suggest their correlation with the Dodgeville surface.

[9] A. C. Trowbridge, "The Erosional History of the Driftless Area," *Iowa Univ. Studies*, 1st ser., No. 40 ("Studies in Nat. Hist.," Vol. IX, No. 3 [1921]), pp. 1–127; R. E. Bates, "Geomorphic History of the Kickapoo Region, Wisconsin," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 819–80.

[10] H. B. Willman and J. N. Payne, "Geology and Mineral Resources of the Marseilles, Ottawa, and Streator Quadrangles," *Ill. Geol. Surv., Bull. 66* (1942), pp. 204–5.

Mahomet Valley and its tributaries were eroded below the upland surface in pre-Aftonian time, as Aftonian and possibly Nebraskan deposits have been identified within the valley in cuttings from wells at Urbana, Champaign County (Fig. 2, cross section *A–A′*, well No. 5), and in southwestern McLean County. In both localities three soils are recognizable, the lowermost or Aftonian being underlain by sand and gravel. The age of the basal sand and gravel is uncertain, and it is considered Nebraskan rather than Aftonian largely because of the absence of humus, the pronounced break at the top of the deposit, and its general similarity to known glacial, rather than interglacial, deposits. Valley cutting thus appears to have been completed by preglacial Pleistocene time. Later modifications of the bedrock surface in the area were probably brought about largely by drainage diversions and only to a minor degree by true glacial corrasion. Glacial erosion by Wisconsin ice was certainly negligible, as there are few instances where the surface drift is not underlain by older glacial deposits.

The dominant glaciofluvial character of the pre-Wisconsin deposits within Mahomet Valley indicates that the valley remained an active drainage line until late Illinoian time. During the early Pleistocene the channel was probably open and cleared of fill, as the pre-upper Kansan sand and gravel in several places rests directly on bedrock (cross sections *A–A′* and *B–B′*, Fig. 2). However, after the deposition of this material, the valley was progressively filled with glacial and interglacial deposits so that by Sangamon time (possibly even by Yarmouth time) it had ceased to function as an important drainage-way and the Sangamon plain crossed it without interruption.

The available evidence indicates that the initial drainage diversion leading to the abandonment of the valley was caused by the advance of the Kansan glacier and that the valley continued only as a minor channel-way during Yarmouth and Illinoian time. The possibility of diversion in pre-Kansan time is opposed by the occurrence of Aftonian and older deposits at elevations between 450 and 500 feet above sea-level within the valley and by the stratified character of all the deposits within the valley that lie below the upper Kansan till. The alternative of diversion by the Illinoian glacier finds some support in the widespread occurrence of middle Illinoian sand along the valley. However, the base of this sand has an elevation of about 550 feet above sea-level, which is 250 feet above the valley-floor and close to the level of much of the upland. This relation, together with the uniform elevation of the Yarmouth soil, suggests that the valley in Illinoian time was a broad sag which followed the general course of Mahomet Valley and received Illinoian outwash but was not an important through-valley. This view is further attested by the fact that the Yarmouth and Sangamon deposits consist largely of peaty soil and alluvial silt and fine sand, most of which probably represents wash from adjacent gentle till slopes.

With the advance of the Wisconsin glacier across the Sangamon plain, all vestiges of the old valley were obliterated, and there is nothing in the present landscape to suggest its existence.

RELATION TO REGIONAL PREGLACIAL DRAINAGE

Numerous well records in southern Benton County, Indiana, suggest that Mahomet Valley continues eastward to join the bedrock valley along the present Wabash River near LaFayette. This interpretation (Fig. 4) is based on well records and bedrock-exposure data compiled largely from the literature and is thus subject to important revisions, although the amount of published data and their agreement are notable.

Low bedrock elevations in southern Benton County were first noted by S. S. Gorby[11] in 1866 and were subsequently verified by Leverett.[12] Three interpretations of these low bedrock elevations have been proposed: (1) the preglacial valley at LaFayette continues west past Oxford (Fig. 4) and thence south to the preglacial valley near Covington;[13] (2) a possible "spur" connects Wabash and Illinois drainage;[14] and (3) the bedrock valley near LaFayette continues south through Fountain County, and the valley in Benton County represents an important western tributary.[15] Concerning the main valley at LaFayette, Fidlar further postulated[16] that this valley continued eastward into Ohio, where it joined the ancient Teays Valley[17] in the central part of the state near Chillicothe (Fig. 1). The course of the valley from LaFayette eastward across northern Indiana to the Indiana-Ohio state line in Adams County is based on numerous well records and in part follows the

[11] "Geology of Tippecanoe County," *Ind. Dept. Geol. and Nat. Res., 15th Ann. Rept.* (1886), p. 76.

[12] "Wells of Northern Indiana," *U.S. Geol. Surv. Water-Supply and Irrigation Paper 21* (1899), pp. 61–66.

[13] Leverett, p. 744 of ftn. 3. (1895).

[14] Clem, ftn. 4 (1911).

[15] M. M. Fidlar, "The Preglacial Teays Valley in Indiana," *Jour. Geol.*, Vol. LI (1943), p. 417.

[16] *Ibid.*, pp. 411–18.

[17] W. G. Tight, "Drainage Modifications in Southeastern Ohio and Adjacent Parts of West Virginia and Kentucky," *U.S. Geol. Surv. Prof. Paper 13* (1903), pp. 1–111.

course of a buried channel previously described by S. R. Capps.[18]

Near the Indiana-Ohio state line the channel coincides with preglacial channels discovered by J. A. Bownocker,[19] and the course southeastward to Chillicothe is based upon the work of Karl Ver Steeg.[20]

west boundary of Tippecanoe County and flows essentially on bedrock to a point about 3 miles south of Covington, where it again enters a buried bedrock valley. In this area Fidlar indicated that the preglacial valley followed a buried channel through Fountain County some distance east of the Wabash River and

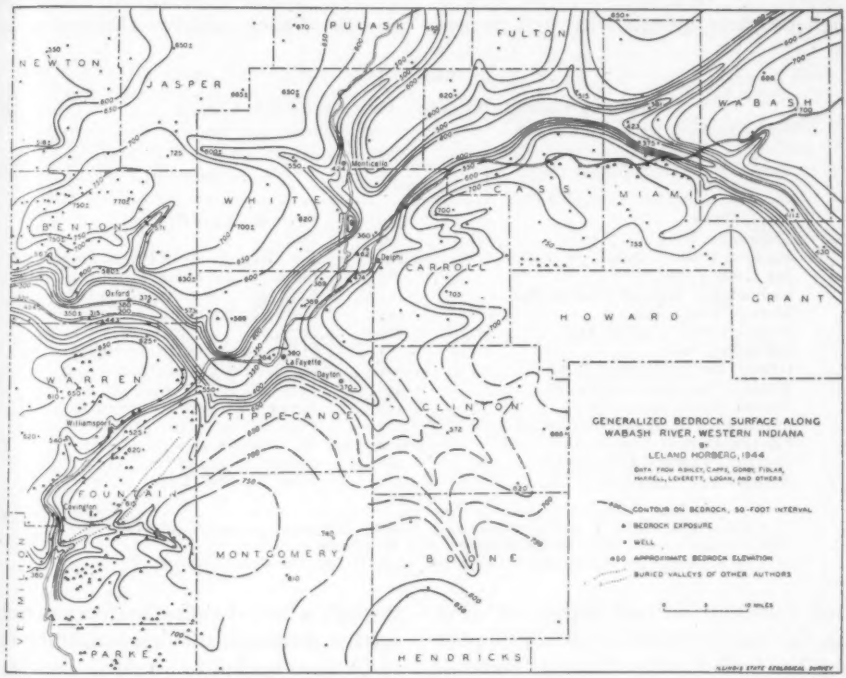

FIG. 4

The course of the ancient bedrock valley south of LaFayette does not follow the present Wabash River, as that stream enters a narrow valley near the joined the present valley south of Covington (Fig. 4). As an alternative hypothesis it is proposed that the main valley turned west near LaFayette, through southern Benton County into Illinois and, as Mahomet Valley, continued west to join the bedrock valley along the Illinois River. The following considerations are offered in support of this interpretation: (1) the valley in southern Benton County appears to be comparable in

[18] "Underground Waters of North-central Indiana," *U.S. Geol. Surv. Water-Supply Paper 254* (1910), p. 26.

[19] "A Deep Preglacial Channel in Western Ohio and Eastern Indiana," *Amer. Geol.*, Vol. XXIII (1899), pp. 178–82.

[20] "The Buried Topography of Western Ohio," *Jour. Geol.*, Vol. XLIV (1936), pp. 918–39.

size to the valley above LaFayette, whereas any buried valley in Fountain County must necessarily be restricted in width; (2) bedrock elevations to the west are lower and more closely spaced than they are to the south, where there is an interval of about 90 miles before comparable low elevations are shown by Fidlar;[21] (3) this interval is an area of high bedrock indicated by well records no reference to an important buried valley within the county.

No satisfactory interpretation of drainage changes in the area south of LaFayette can be made until further information becomes available. It is questionable whether the diversion from Mahomet Valley into the lower Wabash bedrock valley was directly into the present valley above Covington or

TABLE 1

BEDROCK ELEVATIONS ALONG PROPOSED TEAYS VALLEY

Locality	Feet above Sea-Level	Reference
Seary, W.Va.	670	Stout and Lamb*
Chillicothe, Ohio	630	*Ibid.*
Madison County, Ohio	Less than 538	Ver Steeg, p. 925 of ftn. 20 (1936)
Jay County, Ind.	463	Fidlar, p. 416 of ftn. 15 (1943)
La Fontaine, Wabash County, Ind.	411±	Capps, p. 226 of ftn. 18 (1910)
Miami County, Ind.	423	Fidlar, p. 416 of ftn. 15 (1943)
Delphi, Carroll County, Ind.	360±	Logan†
LaFayette, Ind.	384	Fidlar, p. 416 of ftn. 15 (1943)
Oxford, Benton County, Ind.	300	Leverett, p. 757 of ftn. 3 (1895)
Rankin, Vermilion County, Ill.	358	Files, Ill. Geol. Surv.
Paxton, Ford County, Ill.	343	Savage, p. 444 of ftn. 5 (1931)
Mahomet, Champaign County, Ill.	357	Files, Ill. Geol. Surv.
Clinton, DeWitt County, Ill.	Less than 340	Files, Ill. Geol. Surv.
Delavan, Tazewell County, Ill.	288	Savage, p. 444 of ftn. 5 (1931)
Beardstown, Cass County, Ill.	311	Files, Ill. Geol. Surv.

* Wilber Stout and G. F. Lamb, "Physiographic Features of Southeastern Ohio," *Ohio Jour. Sci.*, Vol. XXXVIII (1938), also in *Geol. Surv. Ohio* ("Reprint Ser.," No. 1 [1939]), p. 14.

† W. N. Logan, "The Sub-surface strata of Indiana," *Ind. Div. Geol. Pub. No. 108* (1931), p. 47.

and numerous bedrock exposures[22] (Fig. 4); (4) the published evidence supporting the buried valley through Fountain County is inconclusive,[23] and it is significant that Leverett[24] in a later discussion of the wells of Fountain County makes

[21] Fig. 1, p. 412 of ftn. 15 (1943).

[22] Leverett, "Wells of Southern Indiana," *U.S. Geol. Surv. Water-Supply and Irrigation Paper 21* (1899), pp. 19–20.

[23] The evidence consists of a map and statement by R. T. Brown, published in 1881 without supporting data, in "Fountain County," *Ind. Rept. Geol. and Nat. Res. 11th Ann. Rept.* (1881), p. 92, map facing p. 89.

[24] P. 20 of ftn. 22 (1899).

through a buried valley to the east. Subsurface studies of the deposits filling the valleys are needed to establish the times of important erosion; and until this is done, interpretations will remain uncertain.

Although the details of drainage history in the LaFayette region are not entirely clear, the existing evidence strongly indicates that the main preglacial valley continued into Illinois as Mahomet Valley. If this is true and if the course of the ancient Teays east of LaFayette outlined by previous writers is confirmed, Mahomet Valley represents the course

of the lower Teays River.[25] By this hypothesis Mahomet Valley was eroded by a preglacial master-stream which probably had its source near the eastern scarp of the Blue Ridge in North Carolina;[26] flowed westward across Ohio, northern Indiana, and central Illinois; and finally discharged into the Gulf Embayment through bedrock valleys along the present Illinois and Mississippi rivers. Bedrock elevations (Table 1) along this valley indicate an average gradient of about 7 inches per mile for that portion of it above Beardstown, Illinois.

ACKNOWLEDGMENTS.—This paper is an outgrowth of bedrock-surface and ground-water studies made at the Illinois State Geological Survey under the supervision of L. E. Workman, head of the Subsurface Division, and Dr. George E. Ekblaw, head of the Areal and Engineering Division. The early studies of Pleistocene stratigraphy in the area made by these two men assisted progress of the work, and the manuscript has benefited by their criticism. The aid and suggestions of other members of the Survey staff are also acknowledged.

[25] In this case the name "Mahomet" should be dropped and the valley referred to as the "lower Teays."

[26] Wilbur Stout and Downs Schaaf, "Minford Silts of Southern Ohio," *Bull. Geol. Soc. Amer.*, Vol. XLII (1931), pp. 663–72.

REVIEWS

Handbook for Prospectors and Operators of Small Mines. By M. W. VON BERNEWITZ. Revised by HARRY C. CHELLSON. 4th ed. New York: McGraw-Hill Book Co., 1943. Pp. 547. $4.00.

During the fourteen years before his death, May 18, 1940, three editions had appeared of Mr. von Bernewitz' handbook. These editions not only were very useful to the mining industry but were opportunely issued so that the material was conveniently available through the entire third decade of the present century during the years of the great depression, when so many idle workers with little or no experience at prospecting were turning to it as a means of employment. Owing to the author's wide experience in North America, Australia, New Zealand, and the Netherlands Indies, as well as his journalistic experience, he was well qualified to undertake this work.

In the first three editions of the book von Bernewitz covered essentially the same ground except that in the second edition a chapter was added on geophysics. In the third edition this was withdrawn because it was regarded as too specialized, and it is not restored in the fourth edition.

Mr. von Bernewitz died before his fourth edition went to press. It was revised by Mr. H. C. Chellson, editor of the *Mining Congress Journal*, whose background is nearly similar to that of von Bernewitz, except that his mining experience has been chiefly in North America and Asia.

As the book now stands, the subjects are treated in six parts: (I) equipment, transportation, health, and laws relating to mining; (II) geology, sampling, and measurements; (III) metallic and nonmetallic minerals; (IV) ore dressing and treatment; (V) useful memoranda; and (VI) glossary.

Mining geologists will find (p. 66) a short and interesting list of examples of districts in which geology has proved useful in prospecting and in developing mines, with brief notes on some of them. Among those mentioned are the United Eastern, United Verde Extension, and Miami, Arizona; Chuquicamata, Chili; iron and copper mines in the Lake Superior district; gold mines in Western Australia. Many more could be added to this list.

The reviewer was particularly interested in notes on the Saun concession ("Colbran contact"), which lies near Holkol about 100 miles north of Keije (Seoul), the capital of Korea. The reviewer has not visited the mine but in 1921 was shown maps and other data of the district at the office of the geological survey of Chosen. This district, which was described by Higgins in *Economic Geology* in 1918 (XIII, 1–34), offers a fine example, showing how detailed geologic mapping aided by diligent use of the gold pan may assist in the discovery of a valuable deposit.

The book is compactly but strongly bound with light-weight flexible cover and is designed to stand the rough handling which books carried in the field are likely to get. The style is clear, and the material is well chosen. It contains little that will not be found useful for the inexperienced prospector and much that is conveniently arranged for the more experienced one. It is a very good book.

W. H. EMMONS

Climate of Indiana. By STEPHEN SARGENT VISHER. ("Indiana University Publications, Science Ser.," No. 13.) Bloomington, Indiana, 1944. Pp. 511; figs. 492. $4.00.

This is undoubtedly the most comprehensive study of the climate of a state which has appeared; and, as Indiana is representative of a considerable region, the findings here presented should also have important application well beyond the state boundaries. The volume contains an immense amount of factual material covering all aspects of Indiana's climate, much of which is made graphic on more than four hundred climatic maps of the state (mostly one ninth of a page in size and generally arranged in groups of three, facilitating comparative study). It is a very thorough, painstaking piece of work.

Extending into the field of geology are two chapters: "Climatic Changes and Their Possible Causes" and "Climate and Physiography." These are subjects to which the author has given special attention for many years.

R. T.